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Improved 3D Thinning Algorithms for Skeleton Extraction

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Abstract—In this study, we focused on developing a novel 3D Thinning algorithm to extract one-voxel wide skeleton from various 3D objects aiming at preserving the topological information. The 3D Thinning algorithm was tested on computer-generated and real 3D reconstructed image sets acquired from TEMT and compared with other existing 3D Thinning algorithms. It is found that the algorithm has conserved medial axes and simultaneously topologies very well, demonstrating many advantages over the existing technologies. They are versatile, rigorous, efficient and rotation invariant.

Keywords—three dimensional image; skeleton extraction; Thinning algorithm; topological information

I. INTRODUCTION

3D Skeleton is a very important feature for 3D object representation, pattern recognition and classification in areas such as compact shape description, pattern recognition, robot vision, animation, petrography pore space fluid flow analysis, model/analysis of bone/lung/circulation, and image compression for telemedicine [1-5]. Ideally, 3D skeleton would represent one voxel wide thin lines that retain the connectivity of the original shape, containing both shape features and topological structures of original 3D objects. 3D Thinning is an iterative layer by layer erosion technique for producing medial axis, i.e., skeleton, from 3D objects.

To extract skeleton, i.e., medial axis from an object, three major methodologies are usually employed:

1. Calculation of the three-dimensional Euclidean distance map procedure to generate the skeleton of 3D objects [6, 7];
2. Voronoi diagram [8];  
3. 3D Thinning algorithm [9-14].

The Euclidean distance transform based algorithm provides a straightforward computation which is robust and not sensitive to noise or object boundary complexity, but, the speed of skeletonization is its major drawback. Thinning is an iterative object reduction technique for producing a reasonable approximation to the skeleton in a topology preserving way. During 3D Thinning process, border points of a binary object that satisfy certain topological and geometric constraints are deleted in iterative steps. These points are said to be simple points since their deletion from the image does not affect the topology while some other points must be kept to “preserve the topology”. The entire process is repeated until only the “skeleton” is left. It is very important for Thinning algorithms to preserve connectivity for 3D objects [9, 13, 15]. Otherwise, the skeletons extracted from the object will be disconnected, which is not acceptable in most applications.

There are two major categories of Thinning algorithms in literatures: parallel Thinning algorithms [11, 16-18] and symmetrical Thinning algorithms [19-21]:

1. In parallel Thinning algorithm [18], either points which may be deleted must match at least one amongst several given 3×3×3 masks or templates;
2. It is also allowed to access a neighborhood greater than the 3×3×3 neighborhood centered around a considered point [11, 16, 17];
3. Notion of P-simple points was introduced and found in such a way [19-21] that if these points are deleted in parallel, then the topology is still preserved.

However, it was found that the algorithms based on Ma and Sonka’s Thinning algorithm [11] do not always preserve connectivity of 3D objects [22] while skeletons obtained from symmetric algorithms [21] are well-centered, but not thin. The symmetric algorithms have been conceived in order to produce thin skeletons by deleting some points of minimal non-simple sets, but not all [9].

In this work, we will develop a novel Thinning algorithm, aiming to conserve a voxel wide medial axis (i.e. curve skeleton) and preserve topology, simultaneously. Specially, we incorporate a series of deleting templates and sufficient constraints to overcome these existing limits to extract curve skeleton of porous network from 3D images with various complexities.

II. METHODOLOGY

In this work, the generation of skeleton of the porous network is accomplished by eroding the 3D binary image with morphological Thinning. Our novel Thinning algorithm is designed to satisfy all following five requirements for skeletonizing objects, in addition to previous works [23]:

1. Centeredness satisfaction: Skeleton is geometrically centered within the object boundary, as close as possible to medial axis and looks similar to the original object;
2. Connectivity preservation: The output skeleton should have the same connectivity as the original object, which means that any object in the input image cannot be
split (or disconnected) or completely deleted; any cavity within the object cannot be merged with background or another cavities; creation of new cavity should be avoided; the skeletons should not contain any background elements;
3. Topology must remain constant;
4. The skeleton must be as thin as possible: 1-voxel thin is desirable;
5. They must be invariant to shift, zoom and rotation: geometric and topological characterization of the skeleton obtained must remain constant when the 3D object is moved, scaled or rotated.

A. Basic notions

A voxel \( p \in \mathbb{Z}^3 \) is defined by \((p_1, p_2, p_3)\) with \( p_i \in \mathbb{Z} \) \[21\]. Its three neighborhoods are considered as:

\[
N_{26}(p) = \{ p' \in \mathbb{Z}^3 : \text{Max} \{ |p_1 - p'_1|, |p_2 - p'_2|, |p_3 - p'_3| \} \leq 1 \},
\]

\[
N_{6}(p) = \{ p' \in \mathbb{Z}^3 : \text{Max} \{ |p_1 - p'_1| + |p_2 - p'_2| + |p_3 - p'_3| \} \leq 1 \},
\]
and

\[
N_{18}(p) = \{ p' \in \mathbb{Z}^3 : \text{Max} \{ |p_1 - p'_1| + |p_2 - p'_2| + |p_3 - p'_3| \} \leq 2 \} \cap N_{26}(p).
\]

6-, 18-, 26-neighbors of \( p \in \mathbb{Z}^3 \) are represented in Figure 1. The voxels belonging to \( P \) (the complement of \( P \) in \( \mathbb{Z}^3 \)) are represented as object voxels (background voxels).

B. Deleting templates and additional criteria

Based on the criteria stated above, we modified the templates used in previous pioneer works by taking advantages of both parallel and symmetrical Thinning algorithms and also by using other additional criteria to complete the algorithms.

There are four core templates with the size of \( 3 \times 3 \times 3 \), served in the Thinning algorithm shown in Figure 2, marked as \( A, B, C, D \), respectively. To consider every possibility in terms of voxel configurations, 6, 12, 8, and 12 subsidiary templates in each class are designed as deleting templates as shown in Figure 4, respectively. These templates are symmetrical and without any extended neighbors.

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**Figure 1.** The 6-, 18-, and 26-neighbors of \( p \) are, respectively, represented by black triangles, black squares, and black circles \[21\].

**Figure 2.** Four core templates A, B, C and D: “●” is an object voxel; “O” is a background voxel. A non-marked point is a “don’t care” voxel that can be either an object voxel or a background voxel.

**Figure 3.** Six deleting templates in Class A.

**Figure 4.** 6, 12, 8, and 12 subsidiary templates in each class as deleting templates.
Based on the theory of topology [24], two additional criteria were employed to guarantee that the deletion does not alter the topology of the object in the image, i.e., the objects in the input 3D image are not disconnected by deleting. They are:

1) Judgment of whether an object voxel is simple point or not: if any object voxel in the 26-neighbors of the object voxel currently investigated is 26-connected; if satisfied, the current object voxel is considered as a simple point, a candidate for deleting;

2) Judgment of maintenance of topological relationship: if the background voxel in the 18-neighbors of the object voxel currently investigated is connected and contains at least one background 6-neighbor, the deletion of this object voxel is carried out. Otherwise, its deletion leads to the creation of new cavity, which alters the topology.

C. 3D Thinning

In each iteration, Thinning algorithm would erode the border voxels of the 3D objects layer by layer from the outermost to the inner in a parallel fashion while keeping the topological relations of the objects unchanged until only one voxel wide skeleton is left.

Repeat
1. Mark all object voxels which are 26-adjacent to a background voxel;
2. Repeat
   • Turn every marked object voxel to a candidate for deleting if it satisfies at least one deleting template in Classes A, B, C, or D;
   • Delete the candidature voxel by transforming it into background voxel if it satisfies two criteria in the section 2.3.2;
Until all removable points are deleted, i.e., no voxel can be deleted;
3. Release all marked but not deleted voxels and return to step 1;
   Until no marked voxel can be deleted.
Note that the background points will never be changed to object points in any circumstances.
Finally, the voxels are partitioned into node-link networks for future parameters extraction.

III. RESULTS AND DISCUSSION
To validate the algorithm, 3D image analysis was first performed on a number of computer generated 3D objects with different complexity of topologies and then real-time 3D reconstructed image sets acquired by TEMT from porous membrane network. Simultaneously, we also applied the Thinning algorithm to the objects used by other authors. The results are displayed in Figures 7 (a) and (c).

From Figure 7, it has been shown that medial axes are appropriately generated and all skeletons are one-voxel wide curve-skeletons while the topologies of all 3D objects are preserved by the algorithm. By comparing Figures 7 (k) to (p), it can be found that the Thinning algorithm developed in this work is rotation invariant.

As shown in Figure 8, it is obvious that the algorithm had also given satisfactory results for real 3D images obtained from TEMT and stochastic structure generated by computer modeling.

From Figure 8 (d), the nodes of pore networks can also be identified, which is very useful in topological analysis.

IV. CONCLUSION
To quantify rich 3D structural information of 3D objects, morphological skeleton of porous structure, a lower dimensional representation of the pore space akin to the topological "deformation retract", is usefully the first step.
In this paper, we present a novel 3D Thinning algorithm which takes advantages of both parallel and symmetry Thinning algorithm with new characterization of templates and deleting criteria. To validate the algorithm, 3D image analysis was performed on a number of computer generated 3D objects and real-time 3D reconstructed images of a filtration membrane captured with TEMT.

It was found that the skeleton of 3D objects derived from this Thinning algorithm meets all essential requirements, i.e., they are accurate and one voxel wide; and the topologies of 3D objects were very well preserved. In addition, this algorithm provides a straightforward computation which is robust and efficient, and not sensitive to noise or object boundary complexity. It is also invariant to rotation.

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