**Paper Review Report:**

## A survey on skeletonization algorithms and their applications, Punam K. Saha, Gunilla Borgefors, Gabriella Sanniti di Baja, [Pattern Recognition Letters](https://www.sciencedirect.com/science/journal/01678655)

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1. Outline

This paper presents a survey of skeletonization algorithms and their applications. It categorises skeletonization algorithms into three categories based on their principles and object representation. Subsequently, skeletonization algorithms that fall under these categories are discussed, highlighting their strengths and weaknesses. Further on, this paper discusses algorithms that emphasise topology preservation, parallelization, and multi-scale skeletonization. Lastly, this paper presents the applications of these algorithms and discusses the challenges of assessing their performance.

2. Types of Skeletonization Algorithms

Skeletonization aims to provide a compact representation of an image object by reducing its dimensions into a medial axis and simultaneously preserving the various attributes of the original image such as its topology and geometric properties. Blum et al [1] established the basis of skeletonization algorithms which uses the medial loci of an object to form their skeletons, with the medial axis being defined by a grassfire transformation process. It eventually led to later iterations of skeletonization algorithms being introduced by others. This paper groups these skeletonization algorithms into three categories. The categories are as follows: first are algorithms based on the Voronoi diagram or continuous geometric approaches of point clouds, polygonal, or polyhedral representations of object boundaries; second are algorithms based on the principle of continuous evolution of object boundary curves; and last are algorithms based on digital morphological erosion or location of singularities on a digital distance transform field.

2.1. Continuous geometric and Voronoi diagram algorithms

The most popular approach under this category utilises the Voronoi diagram. The Voronoi skeleton of a polygonal shape is obtained by firstly computing the Voronoi diagram of its boundary vertices and then obtaining the skeleton by taking the intersection between the competed Voronoi diagram with the polygonal shape. This means that in order to obtain the skeleton of any regular object, it must be approximated by a polygon. But in order to create an accurate skeleton an accurate polygon representation will be needed, which would require more vertices. This creates a disadvantage, namely that the increase in vertices produces additional spurious skeletal branches that are not needed for the overall representation of the shape, making it computationally inefficient.

Other methods have thus been generated in order to improve on the Voronoi diagram approach. For instance, Ogniewicz and Ilg [2] were able to derive residual functions to detect spurious branches that were not essential in the skeleton. It has the advantage of enabling the residual function to be used to locate all the spurious branches in a generated skeleton, and with that knowledge made it easier to remove them. Also, Bucksch and Lindenbergh [3] created a new approach based on extracting the skeleton from point clouds using collapsing and merging procedures in octree-graphs. This method not only had the advantage of being computationally efficient, but also allowed the adjustment of the complexity of the skeleton by varying the size of the octree cell.

2.2. Continuous curve propagation algorithms

Continuous curve propagation methods first arose when researchers used Blum’s grassfire propagation alongside a curve propagation model. These curve propagation/evolution processes are modelled by partial differential equations that eventually yield certain singularities that are mathematically referred to as shocks. These shocks are used to form the skeleton. Further on, Siddiqi et al. [4] used the Hamilton-Jacobi equation to compute the outward flux of the vector field of the underlying system (i.e., the object which is to be skeletonised). The singularities at the centre of these flux fields are then used to create the skeleton. The advantage of this method is that it ensures that the skeleton is topologically preserved.

More algorithms were later created that drew inspiration from the curve propagation approach. For instance, Tari et al. [5] used an edge-strength function to extract the object skeletons along the object boundary being computed using a linear diffusion equation. This algorithm was further improved upon by Aslan et al. [6]. A huge advantage of this approach is that it can be used on grey scale images. It also has the advantage of allowing multi-scale regularization of the smoothness of the skeleton. Unlike the method in [4] it has the disadvantage of not allowing skeletons to be topologically connected.

2.3. Digital algorithms

Digital approaches to skeletonization were initially based on simulating Blum’s grassfire propagation in a digital grid as an iterative erosion process. It is important to note that digital algorithms can be further classified into fully predicate kernel based iterative algorithms, and iterative boundary peeling algorithms under topologic and geometric constraints and distance transform (DT) algorithms. The most computationally efficient methods seem to be from the DT category. Some examples from this category would include the DT-based skeletonization in 2D presented by Arcelli and Sanniti di Baja [7] and the algorithm by Borgefors et al [8 - 10], who applied DT based skeletonization techniques in 3D. The main advantages of the DT method include not requiring repetitive image scans and not requiring the management of two buffers, that make these algorithms computationally efficient. Moreover, if a DT-driven voxel erosion strategy is used then the skeletons generated would also remain robust under image rotation. One disadvantage is that this approach makes it difficult to parallelize these algorithms.

3. Specialised Skeletonization algorithms:

As mentioned in the outline, this paper also talks about skeletonization algorithms in the context of topology preservation, parallelization, and multi-scale skeletonization.

3.1. Topology preservation

For topology preservation in skeletonization to occur in both 2D and 3D, simple point constraints need to be applied while eroding each individual pixel or voxel on the object during the process of skeletonization. Lobregt et al. [11] created an algorithm for 3D simple point detection based on the Euler characteristic preservation which has the advantage of being very efficient. However, this algorithm has the disadvantage of not detecting the violation of topology preservation when the deletion of a point instantly splits an object into two and creates a tunnel. Fortunately, this issue was rectified by an algorithm devised by Saha et al. [12-15].

3.2. Parallelization

Early parallel skeletonization algorithms emerged roughly 50 years ago and have produced several 2D and 3D parallel skeletonization algorithms. However, these algorithms have the disadvantage of failing to ensure topology preservation when multiple simple points are deleted in parallel. To resolve this issue, four strategies were adopted namely: the sub iterative parallelization scheme; parallelization using minimal non-simple sets; parallelization using P-simple points; and parallelization using critical kernels. From these four strategies, certain algorithms have been created. For instance, by utilising the second strategy Ma and Sonka [16] were able to devise the first fully parallel skeletonization algorithm in 3D. It has the advantage of being fully parallelized but has the disadvantage of having non-topology preservation. This issue was later fixed by Lohou [17] who devised a better version of Ma’s and Sonka’s algorithm which included all its advantages and excluded its disadvantages.

3.3. Multi-scale skeletonization

Multi scale skeletonization was introduced to solve the problem of extremely bushy and complex branches generated by Blum’s medial axis representation for skeletonization. It did so by incorporating a regularization or significance factor to control the trade-off between the smoothness and simplicity of the medial axis of the generated skeleton. An example of a continuous method is the algorithm devised by Tari et al. [18]. This method has the advantage of a simpler and faster implementation procedure which is applicable to higher dimensions even where gaps exist along the object boundary points. An example of a digital approach is the method by Attali et al. [19] which uses a global lobal shape significance factor to separate the useful branches from the useless and complex. It has the advantage of capturing branches with geometric object information.

4. Summary

This paper encourages parallel skeletonization methods, mainly due to the fact that these methods boast a significant amount of computing efficiency. In terms of performance, it also encourages DT based methods since they show better performance under rotation and at sharp corners. However, this paper emphasises that there is no established performance measure for skeleton algorithms by which an algorithm can be ranked. This is because there is no clear definition of what the “true” skeleton should be and what it should constitute. Therefore, it seems that all these algorithms have their own strengths and weaknesses, and for the time being it would be best not to encourage any particular algorithm, but rather choose which ever is the most well suited for the task.

5 Future Works:

It seems that the biggest problem which needs to be addressed in the future is that of the finalisation of a comprehensive framework for the evaluation of these algorithms. Moreover, any future work in the application of these algorithms, particularly in the biomedical imaging field, would be highly beneficial. This is because many applications like stenosis detection have become especially reliant on these skeletonization algorithms.

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