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A new strategy for skeleton pruning ☆

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ABSTRACT

A new pruning algorithm is introduced to simplify the structure of the skeleton of 2D objects, without affecting significantly the representative power of the skeleton. The concatenations of skeleton branches originating from the end points of the skeleton are examined while building a hierarchical skeleton structure. Skeleton branches that can be interpreted as peripheral branches at any hierarchical level are concatenated with the adjacent skeleton branches that were interpreted as peripheral branches at the immediately previous level. A concatenation extends in the hierarchy for a number of levels related to the number of branch points connecting the successive branches along the concatenation itself. The most internal branch point up to which a concatenation can be pruned without affecting the representative power of the skeleton is determined by using significance measures able to evaluate the loss in object recovery produced by pruning that part of the concatenation. Pruning is performed by removing all the so identified longest prunable concatenations, provided that topology is maintained

1. Introduction

Since the introduction of the Medial Axis Transform MAT [1], the skeleton of a 2D object has been regarded as a powerful shape representation scheme, especially as regards objects that can be interpreted as consisting of the composition of ribbon-like parts. In fact, the skeleton provides rich geometric information as it gives simultaneously locational, directional and size description of the represented object. Moreover, the skeleton can be used in the framework of shape description at multiple scales provided that its branches are associated a significance measure to order them according to their importance.

The ideal skeleton of an object is expected to be characterized by a number of properties: (i) it should be a thin subset of the object, consisting of the union of curves; (ii) it should be symmetrically placed within the object, (iii) it should have the same topological features as the object, i.e., it should have the same number of connected components as the object, and each hole of the object should be surrounded by a loop of the skeleton; (iv) its points should be labeled with their distance from the complement of the object and should be interpreted as centers of discs touching the object boundary in at least two distinct parts, so that object recovery would become possible by computing the envelope of the discs centered on the skeleton points; and (v) the curves of the skeleton, also called skeleton branches, should originate only in correspondence of significant limbs and contour convexities of the object.

Unfortunately, when working in the digital space some of the above properties cannot be fully satisfied simultaneously by the true skeleton S. In particular if S is characterized by linear structure, then complete object recovery cannot be guaranteed whenever the object has parts whose thickness is given by an even number of pixels. Generally, the linear structure of S is the preferred feature, even at the expenses of a non-complete recovery, since it allows one to capture relevant shape information while tracing skeleton branches. On the other hand, the number of object pixels that are not recovered by the envelope of the discs centered on the pixels of S constitutes usually a small percentage of the total number of pixels of the input object.

Another reason that may cause a non-complete object recovery is skeleton pruning. Actually, pruning should be regarded as an integral part of any skeletonization algorithm. In fact, though branches of the ideal skeleton are expected only in correspondence with regions of the object perceived as individually meaningful, the structure of the true skeleton is generally much more complex than this. The skeleton is likely to include a number of branches noticeably larger than the number of object parts perceived as individually significant regions, so that a one-to-one correspondence between skeleton branches and significant object regions cannot be easily established. The existence of scarcely significant branches affects the skeleton whichever skeletonization approach is followed, but is especially relevant when the skeleton is computed by Voronoi diagram based methods [2].

To obtain a skeleton where the above one-to-one correspondence is satisfied, branch significance measures have to be designed to

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distinguish and possibly prune branches of S whose removal does not bias the representative power of the skeleton. Moreover, to avoid altering the topology of S, only peripheral branches of S can be pruned.

Once scarcely significant peripheral branches have been removed, new peripheral branches are likely to characterize the skeleton. In fact, some pixels (called branch points) that in the initial skeleton were meeting points of peripheral skeleton branches may be transformed into tips of new peripheral branches, which may still result as scarcely significant. Thus, to obtain the desired result it may not be enough to apply pruning only to the branches that are initially peripheral in S. The application of pruning should be repeated carefully to avoid that the structure of the final skeleton is excessively simplified. In particular, the loss in representative power due to all the already removed branches coming into the tip of a new peripheral branch should be taken into account when checking such a new peripheral branch for pruning.

It should also be noted that using always the same branch significance measures during all pruning iterations might not produce the desired result. Often, the initial skeleton includes "short" branches that may be characterized by high significance, if this is measured by the same criteria adopted for longer peripheral branches, or for more internal branches. If "short" peripheral branches remain untouched, new peripheral branches – possibly scarcely significant – cannot be originated and the resulting skeleton will not be characterized by the desired manageable structure. To solve this problem, pruning is often implemented as a sequence of two processes: (i) a brute force pruning that does not take into account the context, and (ii) a context dependent pruning where a significance measure is used. Brute force pruning has the role of removing "short" branches so as to allow context dependent pruning to continue along non-significant branches that in the initial skeleton were not peripheral branches.

Pruning can be implemented by following a parallel or a sequential modality [3]. According to the parallel modality, branch points detected in the initial skeleton maintain their status until all initial peripheral branches have been checked and possibly pruned. An advantage of the parallel approach is that the obtained result is independent of the order in which peripheral branches are accessed. However, for iterated pruning, some sophisticated technique is necessary to keep track of the significance of the already removed branches coming into the tip of a current new peripheral branch, so as to avoid an excessive loss in representative power. Alternatively, according to the sequential modality, the status of a branch point is immediately updated as soon as the skeleton branch is pruned. Pruning done according to the sequential approach is generally more conservative, but the obtained result is conditioned by the order in which branches are examined.

Pruning is certainly necessary to obtain a skeleton with a manageable structure, but the object recovered starting from the pruned skeleton is not guaranteed to be complete, especially when pruning is iterated. Thus, care is necessary in designing suitable pruning criteria that simplify the structure of S without dramatically reducing its ability in object recovery.

In this paper, we introduce a new strategy for skeleton pruning, where (concatenations of) branches are removed, provided that their removal does not alter the topology of the skeleton and does not significantly decreases its ability in object recovery. The rest of the skeleton is kept unaltered.

To describe our pruning method, we will refer in the following to the skeleton computed by the algorithm [4], which is based on the use of the ⟨3,4⟩distance transform of the object [5]. We point out that the strategy of the proposed method can be followed for the distance labeled skeleton computed by any other algorithm, provided that suitable modifications of some of the parameters involved in the pruning criteria are accomplished.

The rest of the paper is organized as follows. In Section 2, we list some of the most common pruning criteria and introduce some basic notions. In Section 3, we describe how to build a skeleton hierarchy, where concatenations including skeleton branches are ranked at different levels; moreover, we introduce the significance measures that will be used for the pruning criteria; finally, we illustrate the pruning strategy. The hierarchical structure will allow us to compute a priori the significance of all possible concatenations of skeleton branches while tracing the skeleton. Section 4 describes the experimental part of our work. A brief conclusion is given in Section 5.

2. Pruning methods and basic notions

In the following, we give a sketched description of the most commonly adopted criteria for 2D skeleton pruning and introduce some notions that will be used in the rest of the paper.

2.1. Existing pruning criteria

A comprehensive, even if non recent, survey on different pruning approaches for 2D objects can be found in [6]. There, pruning criteria based on propagation velocity, maximal thickness, radius function, axis arc length, and boundary/axis length ratio are illustrated. Another pruning method, where the maximal loss in object recovery is a priori fixed by the user, is discussed in [4]. There, the significance of a skeleton branch is evaluated in terms of the maximum number of peripheral rows/columns of the object that would not be recovered by the pruned skeleton. More recently, new pruning methods for 2D objects have been suggested in [7,8]. There, contour partitioning via discrete curve evolution and bending potential ratio are introduced; pruning is performed during post-processing, or is embedded into the skeleton computation process. Pruning techniques for the 3D skeleton are also available in the literature. Here, we only mention the 3D pruning method [9] since this has inspired the strategy for the 2D skeleton pruning suggested in this paper. For the sake of completeness, we point out that instead of applying pruning to the skeleton, simplification of skeleton structure can be obtained by performing preliminarily a filtering process to identify in the object suitable anchor points to be used during skeletonization. For example, the MAT has a complex structure since it includes all the symmetry points of the object, but a MAT with simpler structure can be achieved by identifying and marking as anchor points only a suitable subset of the set of the symmetry points [10,11].

Actually, we borrow from [9] the idea of computing a priori the significance of any possible concatenation of branches originating from an end point by building a hierarchical structure where all possible concatenations are recorded. However, in this work we build a different hierarchy as regards the criterion to concatenate more and more internal branches; also the strategy to identify, in correspondence with each tip of S, the longest concatenation whose removal would not significantly diminish the representative power of S is different. In fact, in this work the sequence of branches along a concatenation associated with a given tip is inspected starting from the most internal branch point along the concatenation. Moreover, we do not need to process the peripheral branches of S (i.e., the concatenations at the lowest hierarchy level) by using different criteria with respect to the criteria adopted for the concatenations at higher levels. In other words, we do not need to use brute force pruning, but only make use of context dependent pruning. Finally, the pruning thresholds automatically adapt to the size of the input objects.

2.2. Basic notions

We work with binary images, where the object consists of the pixels with value 1 and the background consists of the pixels with value 0. The 3×3 neighborhood of a pixel p includes the four edge- and the four vertex-neighbors of p. The 8-connectedness and the 4-connectedness are used for the object and the background, respectively.