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Self noise and contrast controlled thinning of gray images

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ABSTRACT

Homotopic grayscale thinning leads to bushy skeleton when applied on noisy images. One way to reduce this phenomenon is the use of the parametric thinning approach. It consists in relaxing the initial constraint by lowering low-contrast crests, peaks and ends, according to a manually selected parameter and under the constraint of ascendant gray level processing. In this work, we propose to control the thinning parameter by considering the lowering decision as a hypothesis testing of a statistical framework. A unitary hypothesis test based on the minimum test statistic is used for the elimination of noise-related peaks and extremities, while a fusion of multiple tests is performed for the insignificant crest lowering decision. This statistical control is first detailed under the assumption of additive Gaussian noise and then, is generalized for noise distributions with known pivotal quantity. The proposed statistical control leads to a local adjustment and a standardization of the parametric thinning process that depends on both the test significance level which is linked to image contrast and to noise standard deviation. The proposed method is tested on synthetic and real images, and compared to two skeletonization methods with proven efficiency.

1. Introduction

Skeletonization is an image transformation that aims to represent objects by their medial axis lines while preserving topology. It results in a one-pixel thin line called *skeleton*. The main approaches of skeletonization are based either on differential geometry or mathematical morphology. The differential methods are widely used in road extraction from aerial image applications. An example of such methods is the line detector of [1]. It models the gray objects as a surface and uses the direction maximizing the concave curvature of the gradient image to localize ridge points. As a result of differential geometry, this direction corresponds to the eigenvector associated with the minimum negative eigenvalue of the Hessian matrix. Other methods combine differential geometry with the region-context [2] or with the snakes edge detection method [3]. Despite the accuracy of these medial axis detectors, their complex parameters adjustment and especially their inability to ensure the connectedness of objects (i.e. homotopy of the skeleton) orients their applicability to regular object lines with few junctions (like roads, vessels, etc…). Concerning the morphology-based skeletonization approaches, thinning methodologies are of primary interest. In fact, homotopic thinning of binary images has been widely investigated in the early nineties [4–6], highlighting their role in feature extraction as an important step in pattern recognition applications [7–9]. Moreover, the interest in homotopic thinning has reached other applications such as road extraction [10,11], medical image processing [12] and biometrics [13,14].

The binary homotopic thinning methods can be either parallel or sequential. A review of parallel approaches has been proposed in [15]. As to the sequential approaches, they proceed by an iterative removal of *simple* pixels that do not change the topological characteristics and preserve unattached branches from deletion by blocking *endpoints* as explained by A. Rosenfeld in [16].

In this work, we are interested in gray tone images where no formal separation of the foreground and background subsets can be assumed. Few parallel thinning approaches were proposed in the grayscale context [17,18], while a larger interest to sequential ones was found in the literature. This interest was motivated by the possible framework extensions of binary sequential thinning to the grayscale case. For instance, one of the possible extensions was proposed by Arcelli and Serino in [19], where the image is decomposed into different subsets with homogeneous gray values via a labeling step. The labeling aims to guide the thinning operations from low to high gray-valued subsets. This technique enables the use of binary thinning notions on each labeled subset. However, it

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requires both a pre-processing and a post-processing in order to obtain a regular skeleton. Another possible way to extend the use of binary notions to the grayscale context was investigated by J. Serra [20] and S. Beucher [21] who proposed a cross-sectional processing of the image gray levels. In fact, the cross-sectional topology provides a decision on whether a pixel is *simple* for the grayscale image, based on the binary cross-section composed of high gray values of the 8-neighborhood. This extension was formalized by G. Bertrand [22] and M. Couprie [23] who proposed a full description of the first gray thinning algorithm. They also introduced the notion of *endpoint* pixel in the grayscale case in order to impede the lowering of branches' extremity, as performed by A. Rosenfeld [16] in the binary case.

Regarding this new topological grayscale thinning framework, homotopy is ensured by the lowering of pixels gray values during the peeling step. After peeling the topographic relief until stability, the expected gray skeleton becomes a gray image composed of regional minima and high-valued pixels that can be considered as “crest pixels”.

In addition to topology preservation, the invariance to noise is an important improvement to address in the grayscale thinning process. In fact, sequential gray thinning methods might maintain insignificant crests, extremities and isolated pixels and thus, results in bushy skeletons. In a recent work, Couprie et al. [24] proposed a grayscale parallel thinning method. They used critical kernels (which were first introduced by Bertrand [25]) in order to propose a parallel thinning strategy guaranteeing image topology preservation. The originality of such method lies in its applicability to the 3D domain, thanks to the use of cubical complex framework. However, the method's sensitivity to the presence of noise produces insignificant crest lines that are post-processed according to their level of contrast.

In order to avoid pre-processing and post-processing steps that may result in a loss of information, Couprie et al. [23] introduced a gray thinning that relaxes the strong constraint of preserving connectedness. The authors relaxed this constraint by merging the *simple* pixel definition with new ones to eliminate insignificant *peaks*, *crests* and *endpoints*. In fact, the algorithm of [23] defined topological notions describing noise-related pixels, imposed an ascendant treatment of pixels according to their gray values, and adjusted the lowering condition using a parameter denoted by λ. Consequently, one may deduce that the processing of such insignificant branches requires an accurate setting of the lowering parameter λ.

A standardized adjustment of the parameter λ becomes necessary for a convenient use of the method. First, we empirically proved the link between this parameter and the noise level in images. By means of subjective tests on skeleton quality, we established a linear dependency of the thinning parameter to the standard deviation of noise [26]. Then, we deduced that the lowering step in the thinning process required a decision that could be assimilated to a statistical hypothesis testing. Therefore, a simple statistical test based on the range statistic was defined in [27] for the parametric thinning in order to select the contrast parameter at the upper bound of the confidence interval. This chosen value allows to eliminate most of the noisy pixels and limits the lowering error rate. The error control is fixed by the well-known significance test levels. It consists of an acceptable error rate of classification (lowerable vs. not lowerable) and offers a meaningful measure for common users of the parametric thinning method.

It was noted, at the end of our initial work [27], that the statistical test which involves the insignificant crests is actually the fusion of multiple hypothesis tests. Therefore, more accurate global hypothesis decomposition needs to be defined for a better confidence level choice for each individual hypothesis.

In the present work, we first revisit the lowering criterion for *peak* and *endpoint* configurations in order to eliminate more efficiently noisy ones. Then, we use a statistical hypothesis test framework to locally adjust the thinning parameter λ for insignificant *peak* and *endpoint*. By building a test based on the lowering criterion, we show that the thinning parameter is no longer global but needs to be set locally as a function of the size and number of connected components detected in the low neighborhood of each pixel. The local thinning parameter values can thus be predetermined at fixed test significance levels and for known noise standard deviation. This unitary test is then used in the fusion of multiple tests as required for crest configurations. The global significance level for these configurations is decomposed into unitary test levels which are determined based on the number of connected components (i.e. tests). Therefore, the proposed adjustment of the thinning is based on the noise standard deviation and on the chosen error decision which reflects the contrast preservation level. In the remainder of the paper, we refer to the proposed method as Self Noise and Contrast Controlled Thinning (SCCT) approach.

In Section 1, we present the evolution of the thinning framework, from binary to classic grayscale algorithm. In Section 2, we focus on the new lowering criterion for *peak* and *endpoint* pixels, then, we present the proposed statistical control of the parametric thinning. We conclude Section 2 by presenting the challenges in terms of algorithmic optimization and topology preservation of the implemented solution. Section 3 is dedicated firstly to a quantitative evaluation of the SCCT method. The results are compared to those of the λ-Skeleton method available in Pink library and to the Differential Line Detector (DLD) presented in [1]. Secondly, illustrations on real images from diverse applications of interest such as biomedical imaging, biometrics and character recognition are given.

2. Topological framework of the thinning: from binary to parametric gray thinning

Multiple binary skeletonization approaches, in particular thinning methods, were proposed in the nineties. Their respective performances were quantitatively evaluated in [4,5] according to criteria linked to skeleton connectedness, geometry preservation and execution times. Applying these methods on grayscale images is possible only through pre-processing and binarization techniques. This might generate a loss of information and thus, degrade the quality and relevance of the obtained skeletons. In order to better control this loss of information, specific thinning methodologies were proposed for grayscale images. As mentioned in the introduction, the most popular approaches that extend binary thinning notions to grayscale image context exploit the cross-sectional topology. In addition, solutions for noise information removal were proposed, such as the parametric thinning introduced in [23].

The understanding of the parametric gray thinning procedure, which is the starting point for our work, needs the definition of topological prerequisites. Describing such a framework starts naturally from the basic notions of the binary case and continues with the gray thinning framework. We choose to follow this evolution and detail, in Section 1.1, the binary thinning principle and its topological definitions. Section 1.2 is dedicated to the topological thinning extension from binary to grayscale domain and then, to the parametric thinning algorithm.

2.1. Binary thinning

A binary image consists of background pixels and foreground pixels also named object pixels. Let us denote this value for the pixel x by $I(x) \in \{0,1\}$, where $\{\ x, I(x)=1\ \}$ refers to object pixels and $\{\ x, I(x)=0\ \}$ refers to the background pixels. When applied to a binary image, the goal of homotopic thinning is to remove object pixels without changing the topological characteristics of the image. Since complementary connectivity between background and foreground must be chosen to respect the Jordan Curve Theorem, 4-connectivity is classically used for the background and 8-connectivity for the foreground.