An adaptive rank-order filter for image enhancement depending on a measure of the local spatial order

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RÉSUMÉ

Ce travail présente une nouvelle méthode de filtrage d'ordre adaptatif pour le rehaussement d'image et pour un traitement de présegmentation, consistant en un lissage avec préservation du détail. La sortie du filtre est choisie entre les niveaux de gris triés de la fenêtre d'observation en fonction d'une mesure locale du degré d'ordre spatial, pour laquelle sont proposées deux définitions. Le but de l'adaptation est de satisfaire à des exigences variables avec les données locales d'image, comme par exemple le lissage du bruit, le rehaussement des transitions et la préservation du détail structuré. Quelques résultats typiques de filtrage, obtenus avec des images naturelles, sont également présentés.

ABSTRACT

This paper describes a new adaptive rank-order filter, to be used for image enhancement or as an early processing stage for segmentation purposes. The filter output is selected among the rank-ordered grey values of the observation window; the output's rank depends adaptively on a local measure of the spatial order, for which two definitions are proposed. The adaptation aims at meeting conflicting filtering requirements, i.e. noise and texture smooothing, edge sharpening, and enhancement of the finely structured detail. Experimental results obtained, with various types of natural images, are displayed; they put into evidence the advantage of these preprocessing filters with regard to edge detection.

1. Image enhancement with conflicting requirements and adaptive rank-order filters

With a broad variety of natural scenes, as for instance with remote sensing or radar views, or with medical and biological images, the enhancement and the early processing for segmentation purposes mostly pose conflicting requirements to the filtering algorithm, namely:

- Grey value plateaus with superposed noise or texture must be smoothed. For segmentation purposes, the smoothing aims not only at noise reduction, but, more generally, at assigning an uniform grey-value label to each pixel of an uniformly textured region. Once having accomplished this step, the region borders can be extracted also by means of a very simple edge detector.
- Step edges must be preserved, and low-steepness edges must be sharpened, thus improving the subjective image quality and the efficiency of further segmentation steps.
- The filter should increase the sharpness and the contrast of spatially ordered detail patterns, as for instance of thin lines or of regular structures. On the other hand, textural patterns with random spatial arrangement should rather be smoothed.

Rank-order filtering ([5]) is a widespread, efficient and computationally simple technique for coping with a great variety of low-level image processing tasks. In adaptive rank-order filtering, some filter parameters, e.g. the coefficients of the ranked grey values, are adapted in dependence of features extracted from the local image data. In this way, it is possible to meet conflicting requirements, arising in different zones of the same image. The adaptive rank-order filtering literature is very vast, and most of the methods concentrate on fulfilling only some of the above requirements. For instance, in [2] an edge-preserving smoothing is obtained by adaptation to the local statistics; in [4] the main point is the preservation of line-shaped details.

This work describes a novel image enhancement approach, based upon the rank filtering technique, which meets the three above requirements in several useful applications. Like in [2], the filter coefficients are adapted in dependence of the image data; this approach is combined with that of [1] of controlling the filter parameters by means of local feature values. However, here the concept of "structured detail" is interpreted more generally than in [1], where it had been associated to a local anisotropy measure.

2. Adaptive rank selection depending on a local measure of spatial order

An L-filter ([5]) is a linear combination of the rank-ordered grey values $x_{(i)}$ $(i = 1 \dots N)$ of the current window U, with coefficients a_i. The filter type considered in this work is a special L-filter (*rank selection filter*), in which only one of the coefficients a_i differs from zero. This choice is motivated in the first place by the requirement, generally not met by L-filters, of avoiding step edge degradation. In this work the selected rank r of the filter output $x_{(r)}$ is not fixed, as for instance in the median filter, but it varies adaptively between 1 and N. A further advantage of the rank-selection filters over the L-filters is their lower execution time, since the latter require a complete ordering of the grey values.

The analysis of a great number of natural images led to the basic idea of this work, namely that of selecting r in dependence of Q $(0 \leq Q \leq 1)$, a local measure of the spatial order (to be defined in the next section), by aid of the following criterion:

(I) In order to exploit the smoothing properties of the median filter, r should lie close to the median $m = (N+1)/2$ when the degree of spatial order is low, i.e. when the local grey value variations are presumably due to noise or texture, and not to ordered patterns associated with important details.

(II) When the degree of spatial order is high, r should lie close to 1 or to N. This aims at exploiting the detail enhancement properties of the extreme-value filter ([3]), whose output is the local maximum or the local minimum, depending upon which one differs less from the grey value of the current pixel.

The proposed filter can be considered as a "soft" version of the extreme-value filter, approaching gradually to its "hard" form as the measure of local spatial order Q approaches to 1. For decreasing values of Q, the output rank r approaches gradually to the median rank m. The rule for determining the rank r is:

$$r = \begin{cases} \text{nearest integer of } [m + Q\,(m-1)] & \text{if} \quad p_0 > \mu \\ \text{nearest integer of } [m - Q\,(m-1)] & \text{if} \quad p_0 \leq \mu \end{cases}$$

where p_0 is the grey value of the current pixel, and $\mu = (x_{(N)} + x_{(1)})/2$ is the mid-range.

3. Some measures of the local spatial order

The measure of local spatial order Q is defined so as to vary between 0 (no order) and 1 (highly ordered pattern). Aiming at a simple and efficient definition of Q, two approaches have been taken: the first one is based on the first-order statistics, which represent the simplest local image description; the second one, which utilizes the second-order statistics, takes account also of the spatial relationships between grey values in U.

Variant 1

The first approach is based on the empirical observation that in real-world images a high spatial order is mostly associated with a sharp bimodal local histogram, with peaks close to the local grey value extrema, while noise and texture are characterized by a rather regular and even distribution. The first-order statistics can be described by the function $x_{(i)}$ of the rank i $(1 \leq i \leq N)$ of the ordered grey values $x_{(1)} \ldots x_{(N)}$, as shown on **Figure 1**, curve a. The $N-1$ normalized increments d_i of $x_{(i)}$ can be treated with the same formalism as the probabilities of occurrence of a discrete set of mutually excluding events.

$$d_i = \frac{x_{(i+1)} - x_{(i)}}{x_{(N)} - x_{(1)}} \quad , \quad 0 \leq d_i \leq 1 \quad , \quad \sum_{i=1}^{N-1} d_i = 1$$

The information contents I, associated with this distribution, is a maximum $I_{max} = \log_2(N-1)$ for equally distributed d_i's. For the considerations exposed above, Q is defined as the complement to 1 of the normalized information contents of the first-order statistics:

$$I = -\sum_{i=1}^{N-1} d_i \cdot \log_2 d_i \qquad Q = 1 + \frac{\sum_{i=1}^{N-1} d_i \cdot \log_2 d_i}{\log_2(N-1)}$$

A high degree of order corresponds to patterns with a low I, as spots, edges and lines or, more generally, to locally binary patterns, in which only the grey values $x_{(1)}$ and $x_{(N)}$ occur; see the curves b (bright spot) and c (edge) in fig. 1. On the other hand, Q is zero when $d_i = (x_{(N)} - x_{(1)})/(N-1) \quad \forall i$, e.g. for equally distributed textures, ramps etc.

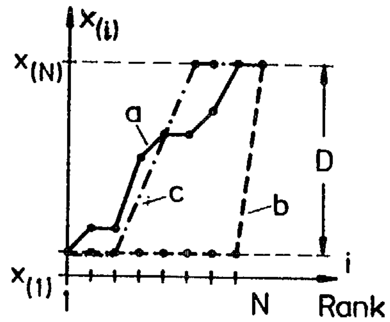

Figure 1

Variant 2

The second definition of a measure of spatial order is based on a more complex image description than the previous one, utilizing the second-order statistics, which take account of the spatial relationships between grey values, and not only of their distribution. The second-order statistics describe the distribution of quantities like $d(c,n)$, i.e. of differences between the grey values of two pixels of U, whose position relative to each other is described by their distance c (integer, comprised between 1 and $L-1$), and by the angle of $n\pi/4$ (n integer, comprised between 0 and 7) with respect to the horizontal axis, as illustrated by the **Figure 2.** Thus the statistics of the quantity $d(c,n)$ depend on the parameters c and n. The criterion underlying to this measure is based upon the observation that patterns with a maximum of local spatial order can be characterized mostly as follows:

(i) All the edges have the contrast $D = x_{(N)} - x_{(1)}$, the highest possible one for the observed local grey value extrema (locally binary pattern).

(ii) The "object" and the "background" of a locally binary pattern have approximately the same area; thus the histogram of d has two equal and sharp modes for $d = 0$ and $d = D$ (see fig. 4a).

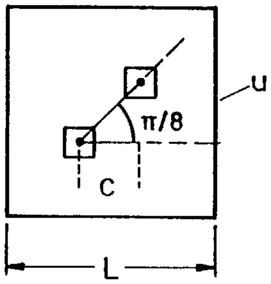

Figure 2

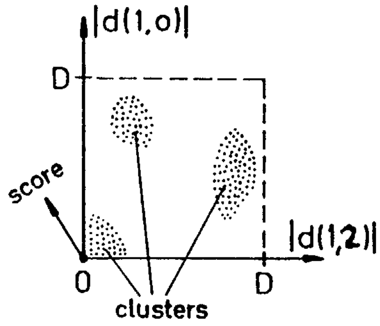

Figure 3

For defining the degree of spatial order on the basis of the second-order statistics, let us consider the 2-dimensional measurement space S_2, spanned by the quantities $|d(1,0)|$ and $|d(1,2)|$, i.e. by the differences between horizontally and vertically neighbouring pixels ($c = 1$). The second-order statistics are then described by the distribution observed in S_2, as shown on **Figure 3**. Empirical observations show that a high cluster concentration in S_2 is associated with a strong spatial order. Thus, one of the clustering quality measures used in pattern recognition can be utilized also as a measure of the degree of spatial order Q.

For the sake of computational simplicity, here no distinction is made between horizontal and vertical differences, and we consider the one-dimensional distribution of the Z samples $d = d(1,0)$ or $d = d(1,2)$, measured in U, with $Z = 2L(L-1)$. The cluster scatter measure has been defined as the standard deviation σ of d. Defining the local contrast $D = x_{(N)} - x_{(1)}$, σ is a maximum ($\sigma_{max} = D/2$) when $Z/2$ of the d's are equal to 0 and $Z/2$ of them are equal to D. This situation corresponds to the highly ordered patterns of **Figure 4a**, with histogram $f(d)$. Thus Q is defined as the normalized standard deviation of d:

$$Q = \frac{\sigma}{\sigma_{max}} = \frac{2\,\sigma}{D}$$

The **Figures 4b-c-d** show other patterns with decreasing spatial order and with values of Q equal to 0.98, 0.86 and 0.66 respectively. Beside the patterns, the corresponding statistics of the differences d (normalized to D) are displayed, and the average α is marked on the d-axis.

The patterns of figure 2a correspond to a maximum of Q also with the Variant 1 of the degree of order. In the filter of Variant 2, Q is a minimum ($\sigma = 0$) if all the d's have the same value, which does not necessarily need to be 0. It follows that not only for a grey value plateau, but also for a checkerboard pattern texture, for which $Q = 0$, the filter performs as a median filter.

4. Experimental results

Both variants of the method described above have been tested with numerous images of natural scenes, and especially with remote sensing and SAR views.

The **Figure 5** shows at the upper left a remote sensing view; the other images are processed with the Variant 1 and different window sizes of $L \times L$: $L = 7$ (upper right), $L = 11$ (lower left), and $L = 17$ (lower right). The smoothing effect, the edge preservation, and the enhancement of the structured details appear evident in all the processed images. With growing window size, the smoothing becomes more intensive, but the detail enhancement is as effective as with small windows. The same kind of remarks can be made for the infrared scene at the upper left of **Figure 6**; for comparison, also the result of the min-max/median filter of [6] ($L = 5$), is displayed at the upper right. In the lower half of this figure, the results of the Variant 1 (lower left, $L = 7$) and of the Variant 2 (lower right, $L = 9$) are compared. The **Figure 7** puts into evidence the advantages of the proposed filters in view of an edge extraction. Here the whole image of fig. 6 has been processed by means of an extremely simple edge detector (current pixel's grey value minus the minimum in a 3×3 neighbourhood), followed by a binarization with a fixed threshold. The prefiltered images of the lower half yield edge maps of sensibly better quality. A further example of the same kind is shown by the **Figure 8**, displaying at the upper left a remote sensing view, and at the upper right the filtered image (Variant 2, $L = 9$). The lower half of this figure shows the edge maps, extracted from the corresponding images of the upper half, in the same way as for fig. 7.

These results show that, in a great number of cases, the presented methods perform a multi-purpose enhancement which fulfills the requirements exposed in the beginning. For instance, in remote sensing views the textured regions (house blocks, vegetation, etc.) are smoothed, but the sharpness of the borders between buildings, vegetation types or crops, and also the linear structures (roads, rivers, highways) are preserved.

The first variant of the method is computationally simpler, but generally less performing than the second one, especially in view of the preservation of details with an ordered structure. Altogether, this approach has proved to be very useful for processing a broad repertoire of critical images at low computation times, in comparison with other adaptive rank-order filtering techniques based on sophisticated models and on complex filter adaptation criteria.

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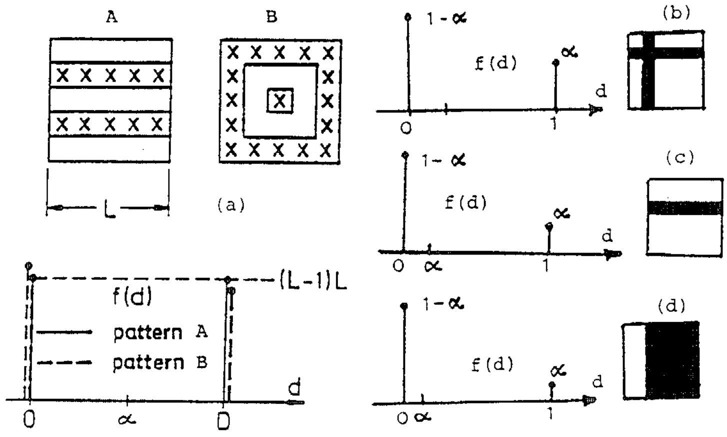

Figure 4

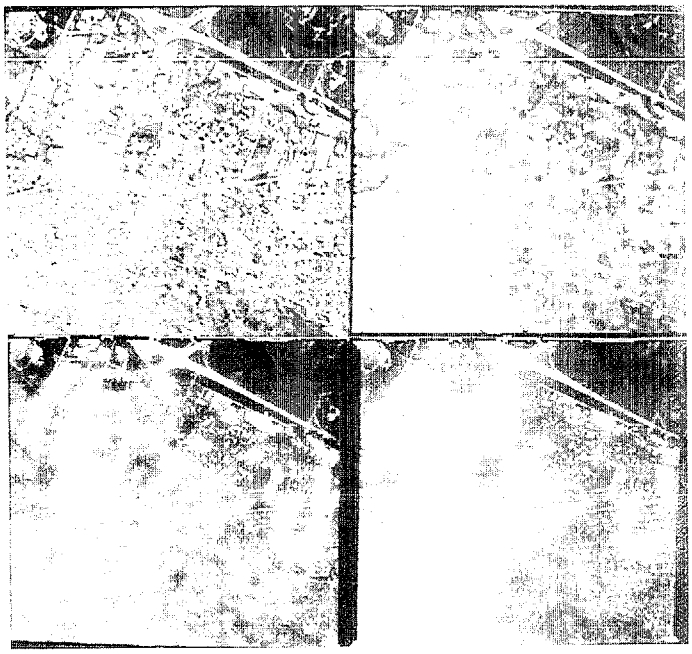

Figure 5

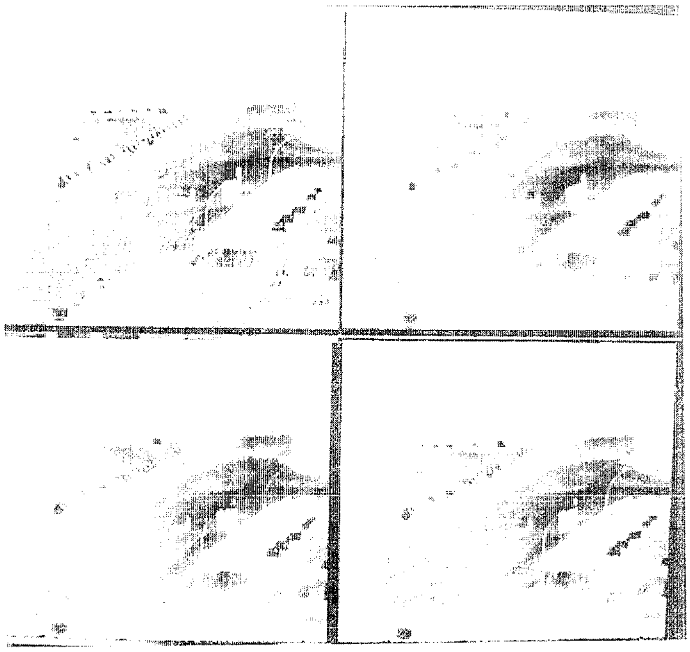

Figure 6

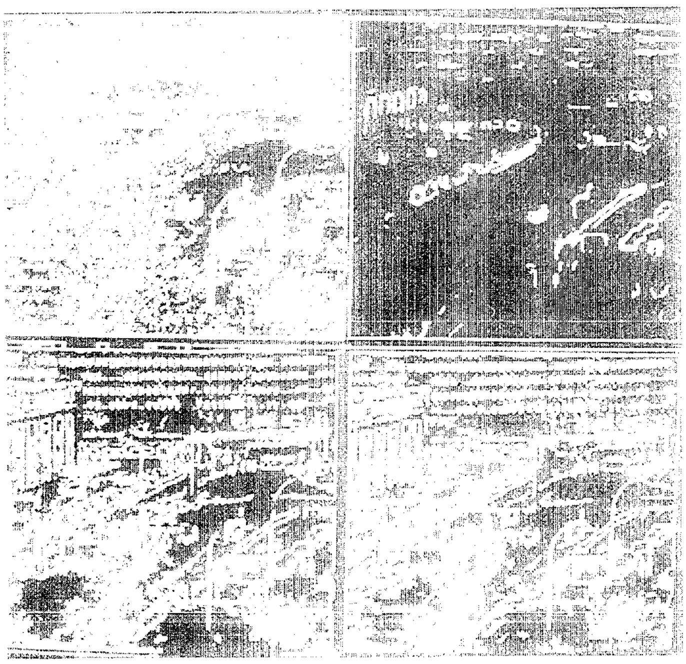

Figure 7

Figure 8