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Nonlocal patch-based method on spatially-variant amoeba morphology for image restoration

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ABSTRACT

In view of the selection of structuring elements problem in morphological filters, this paper presents a new method to generate structuring elements for spatially-variant morphology. This method takes the theory of amoeba morphology as a foundation and new amoeba distances to generate structuring elements for spatially-variant filters are defined. The proposed strategy essentially consists in an amoeba kernel is divided into two parts: one is the patch-based center; another is the pixel-based boundary, the two parts combining both nonlocal patch-based distance and local pixel-based distance. This nonlocal and local configurations make nonlocal patch-based processing method becomes local processing on amoeba structuring element. New amoeba kernels are less flexible at patch-based center than traditional amoebas and their shape is less affected by noises in pilot image. By designing new amoeba structuring element, a new family of morphological filters are derived that have better performance in removing the noise while adaptively preserving the main structures compared with traditional amoeba filters.

1. Introduction

Mathematical morphology (MM) is a set theory-based method of image analysis and plays an important role in many digital image processing algorithms and applications, e.g., noise filtering, object extraction, analysis or pattern recognition [1–4]. MM consists of a set of operators that transform images according to topological and geometrical characteristics. Frequently, a translation invariant approach is used, where the basic operation of dilation (resp. erosion) consists in shifting a probe set called structuring element to each pixel of the image for computing a supremum (resp. infimum). However, it is known that there is an inherent trade-off in spatially-invariant (SI) filters between the noise removal capability of the filter and the feature preservation of the noise-free image. This trade-off is due to the use of a fixed structuring element while morphologically filtering the image. One solution to the denoising problem, then, is to vary the structuring element according to the local characteristics of the image. One of the first studies on spatially-variant (SV) morphology is the work of Beucher [5], which introduced the concept of varying the structuring element according to the position in the image. Other early work on SV mathematical morphology (SVMM) was undertaken by Maragos and Schafer [6], and by Bouaynaya, Charif-Chefchaouni and Schonfeld [7]. Lerallut et al. introduced morphological amoebas [8], as spatially adaptive structuring elements that take into account local structures of the image and where the shape of structuring elements are determined by the amoeba distance. Similar work was done by Grazzini and Soille [9] that proposed spatially variable neighborhoods by utilizing geodesic distances. Welk prove that in the limit of vanishing radius of the structuring elements, iterated amoeba median filtering indeed approximates a partial differential equation related to self-snakes and the well-known (mean) curvature motion equation [10]. An interesting connection between bilateral filtering and adaptive structuring functions was investigated by Angulo [11].

For all these methods of SVMM based on amoeba distance, we call them traditional amoeba morphology or local pixel-based amoeba morphology. As we know, traditional amoeba morphological filters have good performance in preserving the detailed structures in the image. However, the structuring elements are derived from a regularized version of the input image called pilot image [8]. The pilot image is a smoothed version of the input image that suppresses the noise. Generally, there is a large amoeba distance between the noise point (not removed in pilot image) and the pixels around the noise point, thereby limiting the amoeba body's growth. Consequently, the filter based on morphological amoebas preserves edges better, but also is worse at reducing noise.

Recently, nonlocal schemes for image processing have received a lot of attention, starting from the initial paper by Baudes et al. [12]. Salembier in [13] proposed a straightforward generalization

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of nonlocal means filter to morphological filters. Ta et al. [14] introduced a formalism of graph-based nonlocal morphology by generalizing the PDE of dilation and erosion. It is obvious that such approach does not induce a couple of adjoint dilation and erosion, and consequently their products do not involve openings and closings. Velasco-Forero and Angulo in [15] discussed the necessary algebraic properties of nonlocal morphology and introduced an algorithm of sparse nonlocal morphology.

In this paper, new weighted distances to generate structuring elements for amoeba morphological filters are defined. Local pixel-based distance and nonlocal patch-based distance are naturally combined in weighted amoeba kernel. Indeed, the key idea of new amoeba kernel is that the structuring element is divided into two parts: one is the patch-based center, where nonlocal patch-based distance are used by computing the similarity between the central pixel and the pixel in its 8-neighborhoods, another is the pixel-based boundary, where the pixel-based geodesic distance is used by computing the similarity between two adjacent pixels. This new amoeba distance naturally combine local and nonlocal configurations and make nonlocal patch-based processing method becomes local processing on amoeba structuring elements, which guarantee the structuring element is a connected component. By designing new structuring elements, a new family of morphological operators for image processing can be defined. New morphological filters have better performance in preserving the main structures while reducing the noise when applied to vehicle license plate recognition (VLPR) denoising problem, synthetic aperture radar (SAR) image restoration.

2. Related work

2.1. Spatially-variant amoeba morphology

Amoeba morphology is a particular case of SV morphology. Amoeba structuring elements take into account the image contour variations to adapt their shape. By taking advantage of outside information, amoeba morphological filters built upon these structuring elements are very adaptable and can behave in a "more sensible" way than those based on fixed shape structuring elements.

Let D be a subset of the Euclidean space $\mathbb{Z}^2$ that corresponds to the support of the image, and let $T \subset \mathbb{R}$ be a set that corresponds to the gray level values in the image. Then, a gray level image can be represented by a function $f: D \to T$. A 2D image can be represented by a surface, S, embedded in 3D space, with two spatial coordinates and one coordinate that represents the gray level value in the image. A geodesic distance between two points $(x, f(x)), (y, f(y)) \in S, x, y \in D$ is the cost to travel from one point to the other. In other words, a geodesic distance corresponds to the shortest time required to travel from a point $(x, f(x))$ to a point $(y, f(y))$ along the surface S. A path ρ_{xy} that connects two points x and y can be considered as a set $\{x_0, x_1, \ldots, x_n\}$, where $x = x_1, y = x_n$, and $x_i, x_{i+1}, i = 1, \ldots, n-1$ are two adjacent pixels in the path. The rule of judging the pixel belonging to an amoeba is designed as [8]:

$$L(\rho_{xy}) = \sum_{i=0}^{n} 1 + \lambda \times C(x_i, x_{i+1}) \tag{1}$$

The amoeba distance with parameter λ is defined by $d_\lambda(x, y) = \min L(\rho_{xy})$, while a parameter λ regulates a difference between the two incommensurate domains, and as such has a strong influence on the size of the morphological amoebas (given a fixed threshold r). Define the structuring element mapping A as:

$$A_{\lambda,r}(x) = \{y \in D : d_\lambda(x, y) \le r\} \tag{2}$$

Similar work was done by Grazzini and Soille [9] that proposed spatially variable neighborhoods by utilizing geodesic distances, used the following costs between two adjacent pixels x_i and x_{i+1}

$$C(x_i, x_{i+1}) = \frac{1}{2}\left(\left|\nabla f(x_i)\right| + \left|\nabla f(x_{i+1})\right|\right) \times \left\|x_i - x_{i+1}\right\| \tag{3}$$

and

$$C(x_i, x_{i+1}) = \frac{1}{2}\left(\left|f(x_i) - f(x_{i+1})\right|\right) \times \left\|x_i - x_{i+1}\right\| \tag{4}$$

2.2. Nonlocal patch-based image processing

Nonlocal mean filter have been proposed in [12] mainly for denoising applications. The filtering idea consists in computing a weighted average of the input signal in a neighborhood N_x

$$\psi[x] = NLM\left\{f[x]\right\} = \sum_{y \in N_x} w(x, y) f[y] \tag{5}$$

where the weights $w(x, y)$ are defined by computing the similarity between a patch P centered around the pixel x to process and a patch around the pixel at position y. In image processing, such configurations are called "nonlocal", if the patch around the current pixel x is very similar to the patch centered around y, then the weight $w(x, y)$ should be close to one. On the contrary, if both patches are very different, then the weight $w(x, y)$ should be close to zero. As can be seen, the weighted average takes into account mainly pixels that are surrounded by a patch that is similar to the one surrounding the pixel being processed. This is the key point explaining the robustness of this filter. In [12], the weights are defined as follows:

$$w(x, y) = \frac{1}{Z}\exp\left(\frac{-1}{h^2}\sum_{m \in P} g(m)\left\|f[x-m] - f[y-m]\right\|^2\right) \tag{6}$$

In this formula, the similarity between the patches centered around n and k is computed through a weighted Euclidean distance $\sum_{m \in P} g(m)\left\|f[x-m] - f[y-m]\right\|^2$, where m represents the indexes used to scan the patch P and $g(m)$ is a Gaussian kernel, Z is a normalizing constant ensuring that $\sum w(x, y) = 1$. Nonlocal mathematical morphology operators are a natural extension of nonlocal-means in the max-plus algebra, which involves replacing the convolution by the supremum or infimum. Salembier in [13] and Velasco-Forero in [15] are given two forms of non-flat nonlocal morphological erosion and dilation, respectively.

3. New SV morphological filters

3.1. Designing new amoeba kernels

The method of the traditional amoeba construction is that the structuring elements adapt locally to the variation of gray (or color) values, also taking into account the distance to the origin pixel. The distance between two adjacent pixels combining spatial distance and a pixel value distance. It is noteworthy that the structuring elements are derived from the pilot image. As we know, there are still many noises in the pilot image and the pixel-based value distance between the noise point (central pixel) and the pixels around the noise point is large. Consequently, noises in pilot image limiting the amoeba body's growth and have a large impact on the construction of amoeba structuring elements. For example, Fig. 1(a) shows a vehicle license plate image, point x is a noise point (in order to see clearly, only one noise point in this image), the noise point x can result in a failure on the construction of amoeba structuring elements (SE1 in Fig. 1(b)) due to the great difference of pixel-based similarities, as shown in Fig. 1(b). On the contrary, and an elicitation got from the research of nonlocal morphology