Int. J. Electron. Commun. (AEÜ) 69 (2015) 1823–1832

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

An efficient method for salt-and-pepper noise removal based on shearlet transform and noise detection

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ARTICLE INFO

Article history:
Received 12 December 2014
Accepted 9 September 2015

Keywords:
Edge preservation
Logic mask
Salt-and-pepper noise removal
Shearlet transforms

ABSTRACT

The conflicting demands for simultaneous salt-and-pepper noise removal and edge preservation still present an outstanding challenge. In this paper we propose an efficient method for salt-and-pepper noise removal. This method is based on shearlet transform with the help of a logic mask, which is generated by the modified boundary discrimination noise detection (MBDND) algorithm and its inverse. We test our method on four images with noise density ranging from 10% to 95% and compare it against seven other efficient methods by calculating the peak-signal-to-noise ratio (PSNR), the measure of structure similarity (SSIM), and image enhancement factor (IEF). In addition, comparisons of visual quality within the region of interests (ROIs) are also carried out. The significant improvement provided by our method is demonstrated by both numerical evaluation and visual quality.

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1. Introduction

Digital images are often subject to the contamination of impulse noise due to the deficiency in the hardware of communication systems, electro-magnetic inference, etc. Salt-and-pepper noise is one special case of impulse noise, which severely degrades the image quality and hampering further information acquisition. The removal of salt and pepper noise is therefore necessary and important for subsequent processing of images. And in this paper we restrict ourselves to dealing with this type of noise.

Median (MED) filter [1] is very simple to implement and computationally fast. However, due to the fact that it uniformly filters all the pixels by replacing the center values in the windows with median values, the edges and details in images are often seriously blurred or distorted after restoration. This problem gives rise to the two-stage scheme in which corrupted and signal pixels are treated with discrimination. The two-stage scheme has been proven to be more suitable for the removal of impulse noise than the uniform treatments and most of the efficient methods developed afterwards belong to this family. In the first stage of two-stage scheme, the positions of the noisy pixels are detected by certain algorithms, and in the second stage the noisy pixels are replaced with the values yielded by the denoising algorithms.

In our opinion, the two-stage scheme can be improved from two aspects. In the first one, efforts are concentrated on improving the impulse detectors for more efficient impulse noises detection. The impulse detectors play a key role in noise suppression, for false detections may cause the uncorrupted pixels to be filtered, resulting in edge blurring or distortion in images; while miss detections may leave noisy pixels in the filtered results. Therefore, it is very necessary to improve noise detector for filters. For example the adaptive center weighted median (ACWMF) filter [2] identifies the noise pixels by increasing the weight of the pixels in the center of the windows; the improved decision based algorithm (IDBA) filter [3] identifies noise candidates by comparing the center pixel with the minimum and maximum intensity values in a 3×3 window; in Chen and Lien's (Chen) filter [4], the "salt" and "pepper" pixels are recognized by the process of gradual learning; in [5], the noisy pixels are detected by augmenting the ordered difference between the central pixel and its neighbors; The fuzzy impulse noise detection and reduction method (FIDRM) [6] filter and noise adaptive fuzzy switching median filter [7] (NAFSM 2011) use fuzzy principles to determine whether a pixel is corrupted with impulse noise or not; The boundary discriminative noise detection (BDND) [8] and modified boundary discriminative noise detection (MBDND) [9] are also highly effective detectors, which can handle images with noise density of 90%.

In the second point of view, efforts are concentrated on improving the filtering methods for removing noise while preserving edges and details efficiently. The most commonly used method is median

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http://dx.doi.org/10.1016/j.aeue.2015.09.007
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filtering, for instance, the adaptive median filter (AMF) [10] filter uses the median filtering method to remove noise candidates. The main shortcoming of the median filtering method is that it tends to blur image edges especially when noise level is very high. Many other filtering methods are proposed to remove the noise candidates. The IDBA filter replaces the noise candidates by the mean of the four neighborhood processed pixels when the median values themselves are identified as noisy [3]. The Chan et al.'s filter [11] adopts a specialized regularization method to suppress impulses. The Chen and Lien's filter [4] can preserve edges by using a directional correlation-dependent filtering technique based on observing the sample correlations in six different directions [4]. The FIDRM filter [6] and NAFSM filter [7] are another two efficient methods to reduce impulse noise where the fuzzy filtering method is used. To further improve the denoising and edge preserving performance, a total variation diffusion based filter [12] (WUTVI) has also been proposed.

It is well known that the filtering methods can be divided into two categories; one is in the space domain and the other is in the transform domain. 2D fast Fourier transform (2DFFT) is a classic and widely used filtering method in transform domain. 2DFFT can provide the global information in frequency domain of the whole image; however it lacks the ability to locally analyze the details of images. 2D wavelet transform (2DWT) overcomes the shortages of 2DFFT by using wavelet atoms. These wavelets have limited local supports and this feature enables wavelet to better analyze the details than 2DFFT in many occasions; however, the isotropic nature of the 2DWT atom renders it inefficient for the description of curvilinear singularities, namely the edge-like details in images. This problem soon gave rise to the designs of representation systems with anisotropic atoms, such as the curvelet system introduced by Candès and Donoho in 2004 [13] and the contourlet system by Do and Vetterli in 2005[14], etc. These representation systems significantly improved the ability for multi-dimensional analyses; however, they do not exhibit the same advantages wavelets have [15]. Shearlets were introduced in 2006 to provide a framework which achieved the advantages of the previous frameworks and overcame their shortages. Firstly, similar to the wavelet system, the shearlet system can be generated from a mother function by applying a few operators on it [16]. Secondly, for shearlet system, the treatments in continuum domain and discrete domain are consistent [17]. Thirdly, compactly supported shearlet frames bounds are numerically stable [18] and optimally sparse for the approximation of cartoon edges [19]. Due to these advantages, Shearlets has been vastly used in image denoising [20], image fusion [21], image inpainting [22], edge detection [23], etc.

To the best of our knowledge, almost all the filtering methods in the previous two-stage methods belong to the spatial domain family due to the fact that the spatial domain can easily focus the filtering operation only on the noisy pixels in images, while the filtering methods in the transform domain usually need to operate on the whole image.

The main novelty and contributions of this paper include the following aspects:

Firstly, shearlet transform is a state of the art method in transform domain, and to our knowledge it has not been applied to the salt and pepper noise cancellation. The wok in [22] mainly focuses on image inpainting based on shearlet transform, while in this paper we introduce shearlet transform to salt and pepper noise removal. Secondly, Two-stage methods have been proved to be very efficient for removing salt and pepper noise while preserving edges in images. And many works have been carried out to find their potentials. New two-stage methods have been proposed through improving noise detectors or filtering methods. In this paper we propose a new two-stage method by introducing shearlet transform method to the filtering stage. Thirdly, the filtering methods in two-stage schemes only process the noisy pixels. The filtering methods in space domain are simple for processing the pixels with discrimination; therefore almost all the filters in the existing two-stage schemes are in space domain. The filtering methods in transform domain usually need to transform the images by areas or blocks, so it is difficult for these methods to process the noisy pixels only. In this paper, we propose a new technique to enable the filter in transform domain to be applied in the two-stage scheme. Lastly, in comparison with the other seven existing representative two-stage methods, our method provides significant and stable improvements to both visual quality and numerical evaluation results even at extreme noise levels (80% and above).

The rest of the paper is organized as follows. In Section 2 we first provide a flow chart showing the main steps of the proposed method and then we explain each step in details. In Section 3 we test our method on four 8-bit gray scale images with sizes of 512 × 512 pixels, and compare the experimental results against seven other efficient methods in terms of both numerical evaluations and visual quality comparison. Section 4 presents the conclusion.

2. The proposed method

The proposed method mainly includes four steps which are shown as a flow chart in Fig. 1: Firstly, MBDND operates on the noisy image f and a logic mask M is generated; secondly, the noisy image is masked by M to generate a masked image f_{masked}; thirdly, an iterative shearlet transform method is applied on f_{masked} to obtain the filtered image $f_{filtered}$; lastly, the non-noisy pixels are recovered using the logic mask M and its inverse $\sim M$ to obtain the restored image $f_{restored}$. And in the following Sections 2.1–2.4, we expand each step into details respectively.

2.1. Generating the logic mask of an image

Given an image f with sizes of $m \times n$ pixels, which is corrupted by salt-and-pepper noise of certain density, its logic mask M is defined as:

$$M(x_{ij}) = \begin{cases} 0 & x_{ij} \text{ is a noisy pixel} \\ 1 & x_{ij} \text{ is an uncorrupted pixel} \end{cases}, \quad (1)$$

where M has the same size as f.

In our method, the noise detection is accomplished by the MBDND. The following Algorithm I (A.I) shows the steps of MBDND (see [9] for more details about MBDND).

Algorithm I (**MBDND detector**).

1) For each pixel x_{ij} in the image f, impose a 21 × 21 window centering on x_{ij}.
2) Sort the pixels in the window region to an ordered vector v_0 and find the median *med*.
3) Compute the difference vector of v_0, namely the differences between any two neighboring elements in v_0. For the elements at two ends in v_0, who have no elements ahead of or after them, set the differences to zeros.
4) Find the pixels corresponding to the max differences in the intervals of [0, *med*] and (*med*, 255]. And set these two pixels' intensities as the decision boundaries b_1 and b_2 respectively.
5) Classify the pixels in current window into three clusters according to

$$class(x_{ij}) = \begin{cases} pepper & x_{ij} \le min(b_1, m) \\ salt & x_{ij} \ge max(b_1, m) \\ uncorrupted & \text{otherwise} \end{cases}, \quad (2)$$

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