Vector Median Filter for Removal of Impulse Noise from Color Images

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Abstract: This paper presents a vector median filter that incorporates mechanism for the detection of impulses from color images. The vector pixels in a specified window is ranked on the basis of sum of the distances to other vector pixels in the window. The center vector pixel is declared as corrupted if its rank is bigger than a predefined rank and its distance from a nearby healthy vector pixel is bigger than a pre-defined threshold. The corrupted vector pixel is replaced by the vector median. The experimental results show the better performance of the proposed method than a number of existing schemes for color images corrupted by high percentage of fixed-valued and random-valued impulse noises.

Keywords: Vector median filter; center-weighted median filter; rank-conditioned median filter; color impulse noise model; fixed-valued impulse noise; random-valued impulse noise.

1 Introduction

An image is often corrupted by on-off impulse noise of relatively short duration. The impulse is caused by a variety of sources, such as switching, adverse channel environment in a communication system, noise in electronic sensors of the data acquisition system etc. Suppression of impulse noise is an important image processing task.

A number of filtering techniques have been developed in the last few decades for the removal of impulse noise from gray-scale images. A classical technique is the use of the median filter, which is the most popular order statistics filter under the nonlinear filter classes. Originally, the median was widely used in statistics. Tukey introduced it in time series analysis in 1970 [1,2]. In the statistical terminology, impulses outlie from the distribution of the rest of the data and thus, they are called outliers. The reason for success of median filter is its good performance and computational simplicity. The median filter, especially with larger window size, also destroys fine details edges of images due to its rank ordering process [3]. Several techniques have been proposed to improve the performance of the classical median filter in suppressing the impulse noise without destroying the image details.

In multichannel signal, each sample is a vector with multiple components. Color images are examples of multichannel signals. The direct extension of the median filter that is used to remove impulse noise from the gray-scale image to the color images is not straightforward. There are many basic types of subordering principles for ordering the vector data. The most popular ordering principle for color images is vector ordering [4-8]. In vector ordering, a suitable distance measure is selected and the vector pixels in a window are ordered on the basis of the sum of the distances between each vector pixel and other vector pixels in the window. The vector pixel with the smallest sum of distances is the vector median.

The vector median filter and its modifications are generally implemented on all pixels in an image. They tend to alter pixels undisturbed by noise. They modify edges in the cases where the noise ratio is high. As a result, their effectiveness in noise suppression is often at the expense of blurred and distorted image features. A better way to circumvent this drawback is to incorporate some decision-making processes in the filtering framework [9-15]. Most of these approaches are used for gray-scale images only and direct extensions of these to color images are not simple. At each pixel location, it is first determined whether the current pixel is contaminated. Filtering is applied on the corrupted pixels. The corrupted pixels are replaced by the vector median values, while the noise-free pixels are left unaltered. Since not every pixel is filtered, undue distortion can be avoided. A simple but effective impulse detection filter is the center-weighted median filter, which emphasizes the center pixel [16]. It is an improvement over to the weighted median filtern [17,18]. The rank-conditioned median filter is a modification of the median filter that incorporates intelligence to filter only corrupted pixels in the image, in which pixels in the filtering window are ranked according to their magnitudes and the central pixel is considered to be corrupted if it lies outside the trimming range [11,12].

In this work, we propose a vector median filter named vector rank-conditioning and threshold median filter (VRCTMF) that has the capability to detect impulses correctly from color images prior to further processing operations. The initial parts required for the development of the proposed filter is the rank-conditioned vector median filter (RCVMF) and derivations of this and the proposed filter from the vector median filter (VMF) are shown in the proceeding section.

The rest of the paper is organized as follows. Color impulse noise model is explained at Section 2. The proposed filter along with the rank-conditioned vector median filter is formulated in Section 3. Section 4 reports a number of experimental results of the proposed filter. Finally, conclusions are drawn in Section 5.

2 Impulse noise model

It is well known that median filters have good performance in removal of impulse noise from images in the single channel case. Justusson has proposed many probability models of impulse noise [19,20]. Those model are basically used for gray-scale image. However, multichannel signal processing that uses componentwise techniques without considering the dependence between components is suboptimal because the dependence of the component is not utilized. A serious problem in multichannel impulse noise filtering is the lack of appropriate model for such type of noise. Pitas *et al.* have proposed a probability model for a two-channel case [21]. Neuvo *et al.* also have proposed a 3-D impulse noise model [22-25]. The impulse noise may have either very large or small value in that model. It is explained in the following paragraphs.

The model is given below:

$$\mathbf{x} = \begin{cases} \mathbf{s}, & \text{with probability } (1-p) \\ (d, x_2, x_3)^T, & \text{with probability } p_1 p \\ (x_1, d, x_3)^T, & \text{with probability } p_2 p \\ (x_1, x_2, d)^T, & \text{with probability } p_3 p \\ (d, d, d), & \text{with probability } p_a p \end{cases} \tag{1}$$

where $\mathbf{x} = (x_1, x_2, x_3)^T$ is the noisy vector signal, $\mathbf{s} = (s_1, s_2, s_3)^T$ is the noise free color vector signal, d is the impulse value, $p_a = 1 - p_1 - p_2 - p_3$, and $p_1 + p_2 + p_3 \leq 1$. Impulses d can have either positive or negative values but not both. We assume that $|d| \gg s_1, s_2, s_3$ and thus $d - s_1 \cong d - s_2 \cong d - s_3$.

3 Formulation

Consider an RGB (red, green, blue) vector pixel $\mathbf{x}$ at the center of a 3×3 window. Nine vector pixels in the window are given by $\mathbf{x}_i$, where $i = 1,2,\ldots,9$. $\mathbf{x}_1$ is the upper left, $\mathbf{x}_8$, the lower right vector pixels respectively in the window and the remaining pixels are scanned from left to right and top to bottom with the center vector pixel $\mathbf{x} = \mathbf{x}_9$. The set for all vector pixels inside the window is expressed as follows:

$$\mathbf{y} = \{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N\} \tag{2}$$

where $N = 9$.

3.1 Vector median filter

Many filtering methods are available for color images and the vector median is the most popularly used one [4-8]. The vector median filter (VMF) is written as follows:

$$\mathbf{x}_{\text{VMF}} = \text{vector median}(\mathbf{y}) \tag{3}$$

In this method, sums of the distances δ_i of *i*th, $(1 \le i \le N)$ vector pixel from all other neighboring vector pixels in the window are used as a first step for obtaining the vector median and it is expressed as follows:

$$\delta_i = \sum_{j=1}^{N} \Delta(\mathbf{x}_i, \mathbf{x}_j), \quad (1 \le j \le N) \tag{4}$$

where $\Delta(\mathbf{x}_i \mathbf{x}_j)$ represents an appropriate distance measure between the *i*th and the *j*th neighboring vector pixels.

The distances between vector pixels can be calculated in several different ways. The arrangement of all δ_i in ascending order associates the same ordering to the multichannel vector pixels. Thus, an ordering:

$$\delta_1 \le \delta_2 \le \ldots \le \delta_9 \tag{5}$$

implies the same ordering to the corresponding to $\mathbf{x}_i$'s:

$$\mathbf{x}_{(1)} \le \mathbf{x}_{(2)} \le \ldots \le \mathbf{x}_{(9)} \tag{6}$$

where $\mathbf{x}_{(1)}, \mathbf{x}_{(2)}, \ldots \mathbf{x}_{(9)}$ are the rank-ordered vector pixels with subscripts 1, 2, … and 9 as the ranks respectively.

The vector median is defined as the vector that corresponds to the minimum sum of distances to all other vector pixels, i.e. $\mathbf{x}_{\mathrm{VMF}} = \mathbf{x}_{(1)}$ and its rank is 1.

3.2 Rank-conditioned vector median filter

A simple extension to the median filter that incorporates spatial information into the filtering process for the median filter in gray-scale images is the rank-conditioned median filter [11,12]. We extend it into the rank-conditioned vector median filter (RCVMF) for multichannel images. The rank-conditioned vector median filter improves the performance of the vector median filter by outputting the vector median when the rank of the center vector pixel is bigger than a pre-defined rank of a healthy vector pixel that lies inside the window. The rank-conditioned vector median filter can be expressed as:

$$\mathbf{x}_{\mathrm{RCVMF}} = \begin{cases} \mathbf{x}_{\mathrm{VMF}}, & \text{if } r_N > r_k \\ \mathbf{x}, & \text{otherwise} \end{cases} \tag{7}$$

where r_N is the rank of the center vector pixel and r_k, that of the predefined healthy vector pixel inside the window.

Selection of appropriate value of pre-defined rank r_k is very important to decide the compromise between the detail preservation in the vector median output and the removal of impulses from the corrupted images. The most appropriate value the pre-defined rank is 5 in most of the images. Image details are preserved better with a larger value of the rank, at the cost of remaining more impulses in the vector median output. On the other hand, impulses are removed to the maximum extent with a smaller value of the rank, with more blurring effects in the vector median output.

3.3 Rank-conditioning and threshold vector median filter

The filter structure in the above Equation (7) can be further enhanced, incorporating *the threshold mechanism* for the detection of impulses [26,27]. It may not be always true to consider the center vector pixel as corrupted when its rank is bigger than that of a pre-defined vector pixel that lies inside the window, because the geometric distance between the two vector pixels may be very small. Under such circumstances, it is better to take into account the distance between two vector pixels, as an another criterion, in addition to one mentioned in the rank-conditioned vector median filter. In the proposed filter, the center vector pixel is considered to be a corrupted sample if its rank is bigger than that of a pre-defined healthy vector pixel and the distance D between the two vector pixels is bigger than a pre-determined threshold θ. The distance D is calculated as follows:

$$D = \Delta(\mathbf{x}, \mathbf{x}_{(k)}), \tag{8}$$

where $\mathbf{x}_{(k)}$ ($1 < k < N$) is a rank-ordered and healthy vector pixel inside the window.

On the basis of the above formulation, the proposed filter has the following form:

$$x_{VRCTMF} = \begin{cases} x_{VMF}, & if\ r_N > r_k\ \&\ D > \theta \\ x, & otherwise \end{cases}$$
(9)

Incorporating the threshold mechanism in the proposed filter benefits to differentiate between impulses and image details like edges, thin lines, ends of lines etc. The distance D is normally very big if an impulse is present at the center of the window.

4 Experimental results

The test images are 24-bit color images of Lena, Mandrill, Miramar, Airplane, Lake and Tulips. All images are of 512×512 size except Tulips image, which is of 512×768 size. Impulse noises are artificially injected in these images. The performances are evaluated by the visual observation and in terms of the peak signal to noise ratio (PSNR). The PSNR value for the color images is expressed as follows:

$$PSNR = 10\log_{10}\left(\frac{I_{MAX}^2}{MSE}\right) \quad (10)$$

where I_{MAX} is the maximum pixel value of the component of the vector pixel of the original image and MSE represents the mean square error between the filtered image and the original image, which is given below:

$$MSE = \frac{1}{MNS}\sum_{p=1}^{M}\sum_{q=1}^{N}\sum_{t=1}^{S}(y_{p,q,t}^2 - \hat{y}_{p,q,t}^2) \quad (11)$$

where S, M, and N are the number of channels, length and width of the image (S = 3, for color images) respectively, and $y_{p,q,t}$ and $\hat{y}_{p,q,t}$ are the components of the original and filtered vector pixels respectively.

In all cases, a window of 3×3 size is used. The vector median filter, marginal median (MMF) filter, center-weighted vector median filter (CWVMF), rank-conditioned vector median filter and vector signal dependent rank-order mean (VSD-ROM) filter are used for comparison. Thresholds used in different filtering schemes are tuned respectively for different degraded images. All algorithms are implemented recursively.

The first set of experiments are conducted to study the efficiency of the proposed filter in removal of fixed-valued impulse noise and random-valued impulse noise generated by the color impulse noise model explained in Section 2, at different noise ratios. The results are taken using Lena image with threshold values of 30 and 20 for fixed-valued impulse noise and random-valued impulse noise respectively, and two graphs are plotted in Figs. 1(a) and 1(b), where the noise ratios for all types of impulses range from 10% to 60%. It has been seen vividly from these graphical figures that the proposed filter provides superior results to the other filters mentioned in our paper in removal of impulse noises at all noise ratios. It is found experimentally that a single pass filtering is sufficient to remove impulses when the noise ratio is below 50% and multiple passes are required when the ratio is above it.

We list some results in Tables I and II. These tables present the comparative results of the proposed filter in removal of the impulse noises generated by the color impulse noise model at p_1 = 25%, p_2 = 25%, p_3 = 25%, p_a = 25% and p = 20%. The better performance of the proposed filter is seen from the tables.

Fig. 2 shows the restoration results of different filtering methods applied on Lena image corrupted with 60% random-valued impulse noise (p_1 = 25%, p_2 = 25%, p_3 = 25%, p_a = 25% and p = 60%). More blurring effects are observed in the filtered outputs of VMF and MMF. The performance of the VSD-ROM filter is better than those of VMF and MMF, but inferior to that of the proposed filter. It is observed from the filtered output of the proposed filter that it has the ability to preserve image features better than the other filters while removing impulses from the image.

Fig. 3 presents a comparison between the conventional VMF and the proposed filter in removal of 60% fixed-valued impulse noise from Lena image. More blurring and more impulse left unfiltered are seen in the case of the VMF.

5 Conclusions

In this work, we have presented a vector median filter, which has the capability of detection of impulses from color images prior to filtering. It has been observed from the experimental results and visual observation that the performance of the proposed filter is better than those of VMF, MMF, CWVMF, VSD-ROM filter and VRCTMF in removal of impulse noises generated by the different types of impulse noise models. It is due to the ability of the detection mechanism of the proposed filter to detect the corrupted pixels rightly. Inclusion of the threshold mechanism for detection of corrupted pixels in the vector median filter has enhanced the performance of the proposed filter. Moreover, the proposed scheme gives a very stable performance over a wide variety of images.

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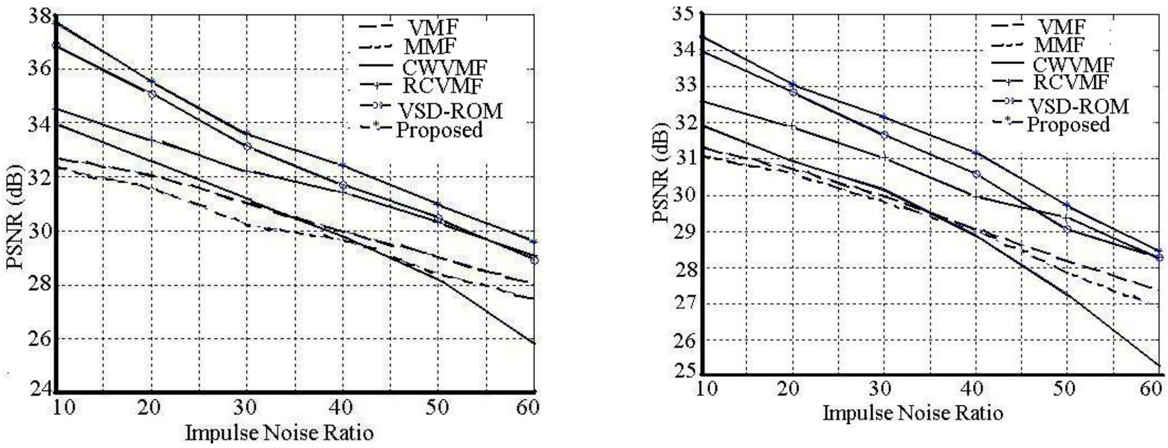

(a) (b)

Fig.1. Performance comparison of VMF, MMF, CWVMF, RCVMF, VSD-ROMF and VRCTMF for removal of impulse noise from Lena image: (a) Fixed-valued impulse noise (b) Random-valued impulse noise.

TABLE I : Performance comparison of VMF, MMF, CWVMF, RCVMF, VSD-ROM filter and RCTMF in removal of 20% Fixed-valued impulse noise generated (p_1 = 25%, p_2 = 25%, p_3 = 25%, p_a = 25% and p = 20%).

Fixed-valued Impulse Noise						
	Lena	Mandrill	Miramar	Airplane	Lake	Tulips
VMF	32.02	22.57	25.90	32.27	27.07	32.32
MMF	31.60	22.20	25.44	31.53	26.90	31.76
CWVMF	32.60	22.77	26.83	32.57	28.12	33.31
RCVMF	33.37	23.36	27.14	33.55	28.86	34.35
VSD-ROMF	35.08	23.37	27.89	34.12	28.61	33.66
RCTVMF	35.57	23.64	28.54	34.86	29.22	34.36

TABLE 2 : Performance comparison of VMF, MMF, CWVMF, RCVMF, VSD-ROM filter and VRCTMF in removal of 20% Random-valued impulse noise generated (p_1 = 25%, p_2 = 25%, p_3 = 25%, p_a = 25% and p = 20%).

Random-valued Impulse Noise						
	Lena	Mandrill	Miramar	Airplane	Lake	Tulips
VMF	30.76	22.46	25.95	32.35	27.11	32.51
MMF	30.60	22.15	25.45	31.53	26.93	31.74
CWVMF	30.93	23.09	26.84	32.20	28.22	33.36
RCVMF	31.90	23.28	27.13	33.37	28.88	34.58
VSD-ROMF	32.86	23.34	27.93	34.17	28.61	33.73
RCTVMF	33.06	24.27	28.84	34.37	30.08	34.81

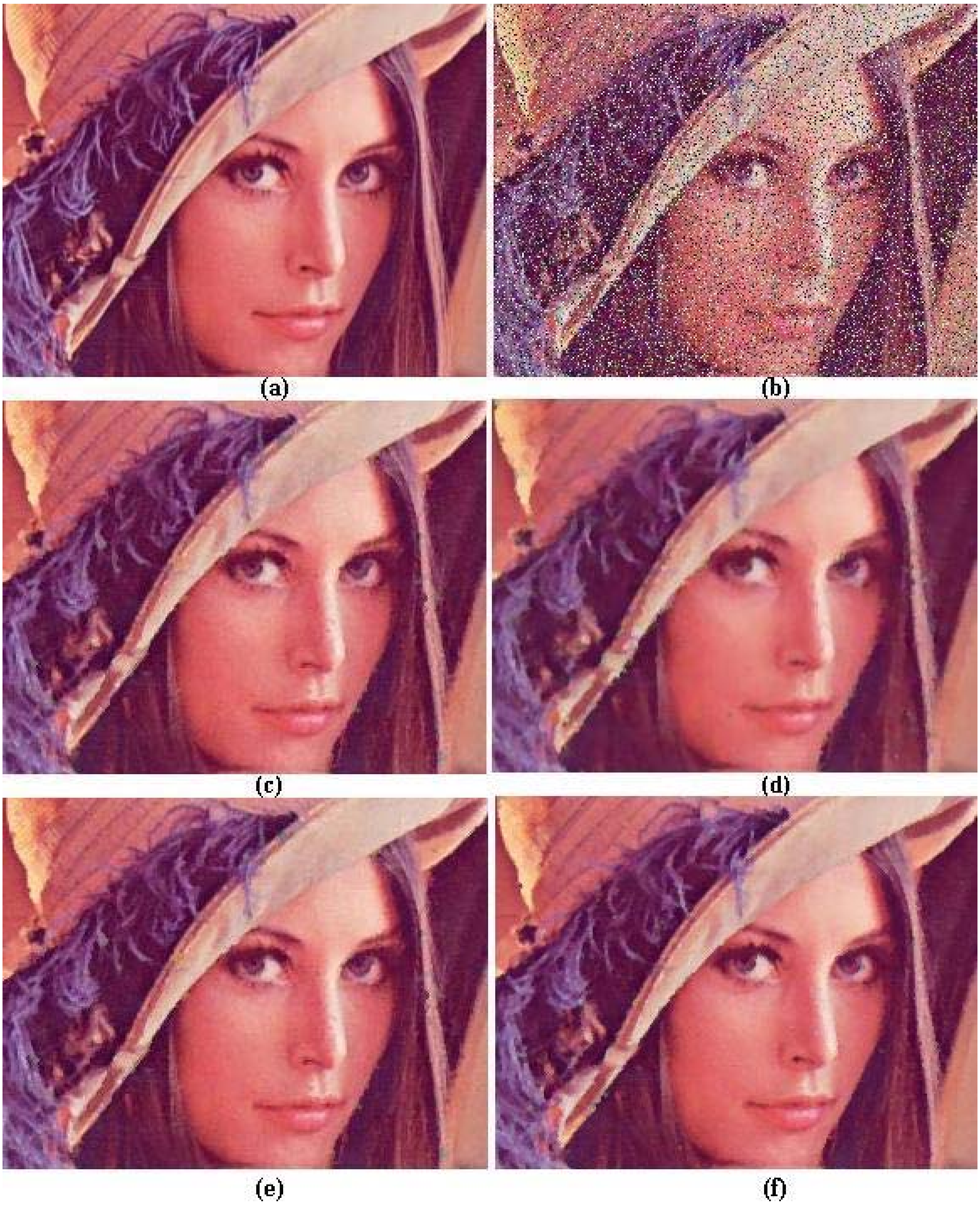

Fig. 2: Performance comparison of VMF, MMF, VSD-ROM filter and VRCTMF in removal of 60% Random-valued impulse noise generated (p_1 = 25%, p_2 = 25%, p_3 = 25%, p_a = 25% and p = 60%) – (a) Original Lena Image, (b) With 20% random-valued impulse noise, (c), (d), (e) and (f) are filtered outputs of VMF, MMF, VSD-ROM filter and VRCTMF respectively.

Fig. 3: (a) Original Lena image, (b) Lena with 60% fixed-valued impulse noise, (c) Output of VMF, (d) Output of VRCTMF, (e) and (f) are the differences between original image and (c) and (d) respectively.