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ADAPTIVE 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 predefined 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 impulse noise.

Keywords: *Vector median filter; center-weighted median filter; rank-conditioned median filter; color impulse noise model; threshold; two-sided fixed impulses model; bit error model; color impulse noise model.*

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 greyscale 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 greyscale 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

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ordering [4,5,6,7,8]. 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 [9,10,11,12,13,14,15]. Most of these approaches are used for greyscale 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 filter.[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. Three different types of impulse noise models are explained in brief 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 MODELS

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 greyscale image. Two models from him are used in our paper for removal of impulse noise from multichannel images. It is assumed in those models that all component impulse noises in each channel are independent of each other. The models are two-sided fixed impulses model and bit-error model. 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.* [22] also have proposed a 3-D impulse noise model [22,23,24,25]. That model is explained in the following subsection.

2.1 TWO-SIDED FIXED IMPULSES MODEL

The impulse noise may have either very large or small value. Such type of noise is known as salt and pepper noise for greyscale images.

Let x_c, (where c = 1, 2 or 3) be a pixel component of the vector pixel at the center of the sliding window in any one of the channels of a multichannel image.

At every signal component an error occurs with probability $p + q$ independent of both the error at other signal points and the values of the original signal. An erroneous point can have one of two extreme values in this model, that is i.e. either l or h, where l is 0 and h is $2^B - 1$ for a B bits per pixel component with probabilities of $\frac{p}{p+q}$ for l and

$\frac{q}{p+q}$ for h respectively. Then, the model can be expressed in the following way:

$$x_c = \begin{cases} l, & \text{with probability } p \\ h, & \text{with probability } q \\ s_c, & \text{with probabilty } 1-p-q \end{cases} \quad (1)$$

where s_c is a noise free pixel component.

2.2. BIT ERROR MODEL

More realistic case of impulse noise is one with the amplitude of impulse noise ranging between 0 and $2^B - 1$.

Let

$$s_c = k_1 2^{B-1} + k_2 2^{B-2} + ... + k_{B-1} 2 + k_B, \quad (2)$$

where k_r for all $r = 1,2,\ldots,B$ be the original signal values quantized to B bits. Assume that the bit errors occur with probability p independent both of the errors at other signal values and errors in this signal value. Then the corrupted signal values are of the form:

$$x_c = k_1^* 2^{B-1} + k_2^* 2^{B-2} + ... + k_{B-1}^* 2 + k_B^*, \quad (3)$$

where

$$k_r^* = \begin{cases} k_r, & \text{with probability } 1-p \\ 1-k_r, & \text{with probability } p \end{cases} \quad (4)$$

2.3. COLOR IMPULSE NOISE MODEL

The number of multivariate impulse noise model for the study of the effect of noise in color image processing is less. Neuvo *et al*. have proposed a color impulse noise model that is given below:

$$\mathbf{x} = \begin{cases} \mathbf{s}, & \text{with probability } (1-p) \\ (d, s_2, s_3)^T, & \text{with probability } p_1 p \\ (s_1, d, s_3)^T, & \text{with probability } p_2 p \\ (s_1, s_2, d)^T, & \text{with probability } p_3 p \\ (d, d, d), & \text{with probability } p_a p \end{cases} \quad (5)$$

where $\mathbf{x}$ 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 $i = 1,2,...,9$. $\mathbf{x}_1$ 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:

$$\mathbf{y} = \{\mathbf{x}_1, \mathbf{x}_2, ..., \mathbf{x}_N\} \quad (6)$$

where $N = 9$.

3.1. VECTOR MEDIAN FILTER

As already mentioned in Section I that the procedure that is used to find out the median of the greyscale images cannot be used directly in color images. Many filtering methods are available for color images and the vector median is the most popularly used one [4,5,6,7,8]. The vector median filter (VMF) is written as follows:

$$\mathbf{x}_{\text{VMF}} = \text{median}(\mathbf{y}) \quad (7)$$

In this method, sums of the distances δ_i of ith, $(1 \leq i \leq N)$ 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:

$$\delta_i = \sum_{j=1}^{N} \Delta(\mathbf{x}_i, \mathbf{x}_j), \quad (1 \leq j \leq N) \quad (8)$$

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

The distances between vector pixels can be calculated in several different ways. The most commonly used measure is the L_1 norm (City block distance), which provides better results when non-correlated noise is present [8]. However, a more general class of vector median is obtained by using the L_P norm with the Euclidean distance (L_2 norm), the method of choice in many practical applications that has been proven to be better when the noise in signal components is correlated.

The arrangement of all δ_i in ascending order associates the same ordering to the multichannel vector pixels. Thus, an ordering:

$$\delta_1 \le \delta_2 \le ... \le \delta_9 \quad (9)$$

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

$$\mathbf{x}_{(1)} \le \mathbf{x}_{(2)} \le ... \le \mathbf{x}_{(9)} \quad (10)$$

where $\mathbf{x}_{(1)}, \mathbf{x}_{(2)}, ... \mathbf{x}_{(9)}$ 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 greyscale 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 predefined rank of a healthy vector pixel inside the window. The rank-conditioned vector median filter can be expressed as:

$$\mathbf{x}_{\mathrm{RCVMF}} = \begin{cases} \mathbf{x}_{\mathrm{VMF}}, & \text{if } r_N > r_k \\ \mathbf{x}, & \text{otherwise} \end{cases} \quad (11)$$

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 predefined 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. 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 (11) 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 predefined vector pixel inside the window, because the 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 predefined 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:

$$D = \Delta(\mathbf{x}, \mathbf{x}_{(k)}), \quad (12)$$

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:

$$\mathbf{x}_{\mathrm{RCTVMF}} = \begin{cases} \mathbf{x}_{\mathrm{VMF}}, & \text{if } r_N > r_k \;\&\; D > \theta \\ \mathbf{x}, & \text{otherwise} \end{cases} \quad (13)$$

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. Three different types of impulse noises, generated by three different types of impulse noise models are used for testing. 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:

$$PSNR = 10\log_{10}\left(\frac{I_{MAX}^2}{MSE}\right) \qquad (14)$$

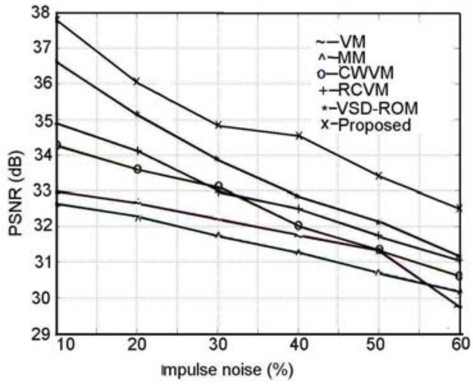
where I_{MAX} is the maximum pixel value of the component of the vector pixel of the original image and MSE represents the mean square error between the filtered image and the original image, which is given below:

$$MSE = \frac{1}{MNS}\sum_{p=1}^{M}\sum_{q=1}^{N}\sum_{t=1}^{S}(y_{p,q,t}^2 - \hat{y}_{p,q,t}^2) \qquad (15)$$

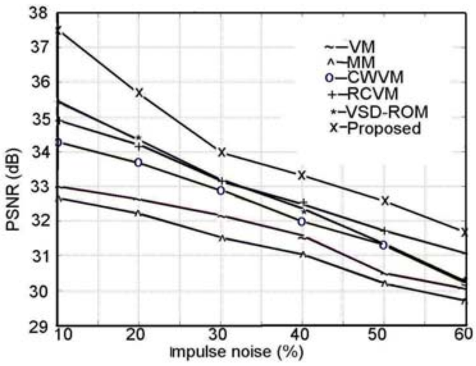
where S, M, and N are the number of channels, length and width of the image (S = 3, for color images) respectively, and $y_{p,q,t}$ and $\hat{y}_{p,q,t}$ are the components of the original and filtered vector pixels respectively.

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 [15,18,28]. Thresholds used in different filtering schemes are tuned respectively for different degraded images. All algorithms are implemented recursively.

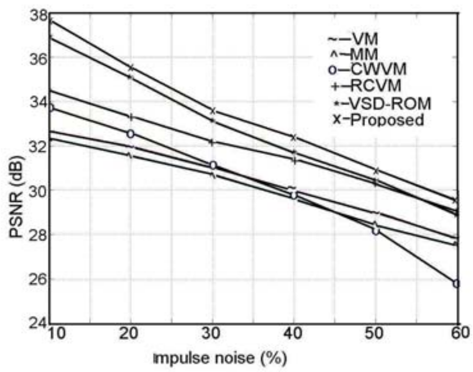
The first set of experiments are conducted to study the efficiency of the proposed filter in removal all types of impulse noises generated by three different types of impulse noise models, at different noise ratios. The results are taken using Lena image and three graphs are plotted in Figs. 1(a), 1(b) and 1(c), where the noise ratios for all types of impulses range from 10% to 60%. It is seen vividly from these graphical figures that the proposed filter provides superior results to the other filters mentioned in our paper in removal of all types 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.



(a)



(b)



(c)

Fig.1. Performance comparison of VMF, MMF, CWVMF, RCVMF, VSD-ROMF and RCTVMF for removal of impulse noise, generated by different types of noise models from Lena image: (a) Two-sided fixed impulses model, (b) Bit error noise model and (c) Color impulse noise model.

We list some results in Tables I, II and III. These tables present the comparative results of the proposed filter in removal of the impulse noises generated by two-sided fixed impulses model, bit error model and color impulse noise model respectively from various images degraded by 20% impulse noise (6.67% noise per channel for the first two models and p_1 = 25%, p_2 = 25%, p_3 = 25%, p_a = 25% and p = 20% for the last model). The better performance of the filter is seen in terms of PSNR (dB) from tables.

Fig. 2 shows the restoration results of different filtering methods applied on Miramar image corrupted with 20% impulse noise (p_1 = 25%, p_2 = 25%, p_3 = 25%, p_a = 25% and p = 20%), generated by color impulse noise model. More blurring effects are observed in the filtered outputs of VMF and MMF. Image features are preserved to a better extent in cases of filtered outputs of CWVMF and RCVMF, but at the cost retaining more impulses in the results. The performance of the VSD-ROM filter is better than those of VMF, MMF, CWVMF and RCVMF, 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.

TABLE I : Performance comparison of VMF, MMF, CWVMF, RCVMF, VSD-ROMF and RCTMF in removal of impulse noise from various images, corrupted with 20% impulse noise generated by two-sided fixed impulses noise model (6.67% noise per channel).

Two sided fixed impulses model						
	Lena	Mandrill	Miramar	Airplane	Lake	Tulips
VMF	32.67	22.38	25.59	30.00	26.72	32.78
MMF	32.29	22.42	25.72	31.97	27.46	32.69
CWVMF	33.61	23.97	27.37	33.82	28.71	34.96
RCVMF	34.13	23.78	27.44	33.86	27.29	35.11
VSD-ROMF	35.32	23.88	25.90	32.03	26.90	34.04
RCTVMF	35.82	24.14	28.15	34.44	29.96	35.83

TABLE II : Performance comparison of VMF, MMF, CWVMF, RCVMF, VSD-ROMF and RCTMF in removal of impulse noise from various images, corrupted with 20% impulse noise generated by bit error noise model (6.67% noise per channel).

Bit error model						
	Lena	Mandrill	Miramar	Airplane	Lake	Tulips
VMF	32.63	22.24	25.55	30.33	25.92	32.20
MMF	32.24	22.30	25.69	30.42	26.32	32.58
CWVMF	33.69	23.77	27.30	31.90	27.31	34.20
RCVMF	34.21	23.50	27.37	31.80	27.58	34.40
VSD-ROMF	34.68	23.57	26.00	31.08	26.50	33.95
RCTVMF	35.70	24.07	28.89	32.19	28.19	35.26

TABLE III : Performance comparison of VMF, MMF, CWVMF, RCVMF, VSD-ROMF and RCTMF in removal of impulse noise from various images, corrupted with 20% impulse noise generated by color impulse noise model (p_1 = 25%, p_2 = 25%, p_3 = 25%, p_a = 25% and p = 20%).

Color impulse noise model						
	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

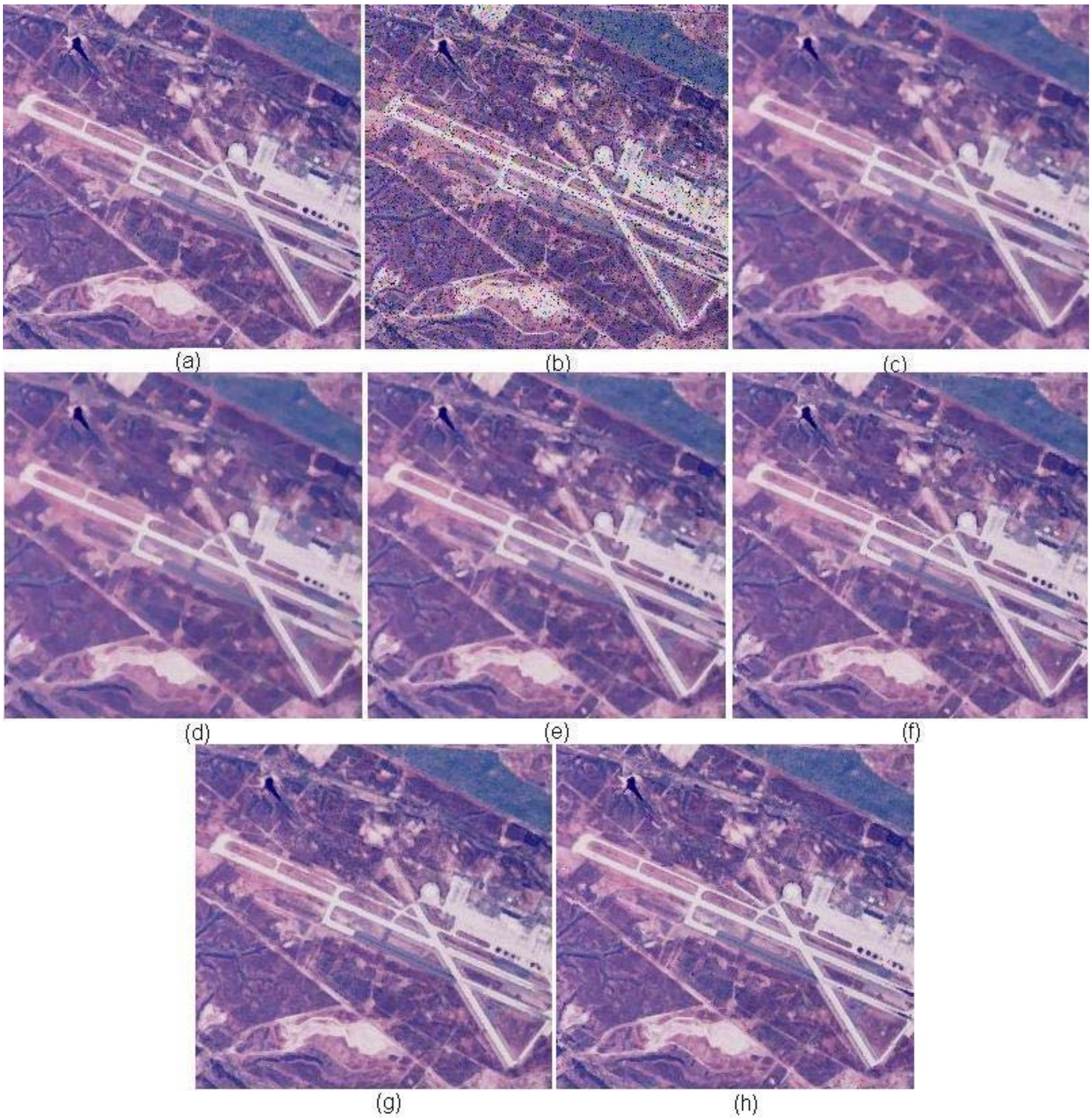


Fig.2(a). Original Miramar image, **(b)** With 20% (p_1 = 25%, p_2 = 25%, p_3 = 25%, p_a = 25% and p = 20%) impulse noise, generated using color impulse noise model, **(c) (d), (e), (f), (g)** and **(h)** are the filtered outputs of VMF, MMF, CWVMF, RCVMF, VSD-ROMF and RCTVMF respectively.

Fig. 3 shows the experimentation results on Lena image corrupted with 60% impulse noise (20% per channel), generated by bit error model. It is seen clearly from the restored signals that blurring effect is less for the proposed filter in comparison with those of other filters.

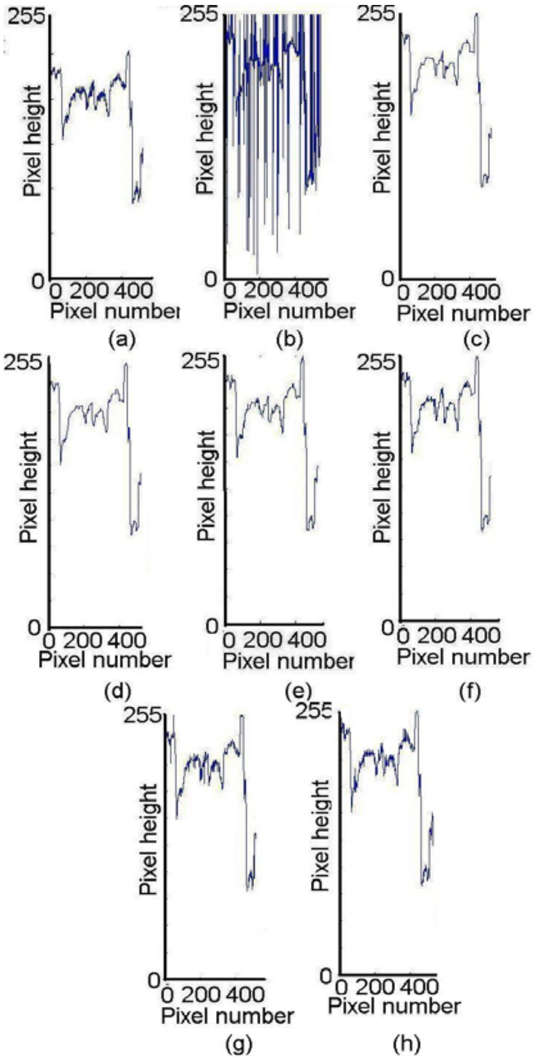


Fig. 3 Experiment with 1-D signal: (a). Original signal from Lena image, (b). Signal with 60% impulse noise (20% noise per channel generated using bit error model) and (c), (d), (e), (f), (g) and (h) are the filtered outputs of VMF, MMF, CWVMF, RCVMF, VSD-ROMF and proposed filter respectively.

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-ROMF and RCVMF in removal of impulse noises generated by three 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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