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Fast and efficient median filter for removing 1–99% levels of salt-and-pepper noise in images

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ABSTRACT

This paper proposes a new median filter using prior information to capture natural pixels for restoration. In addition to being very efficient in logic execution, the proposed filter restores corrupted images with 1–99% levels of salt-and-pepper impulse noise to satisfactory ones. Without any iteration for noise detection, it intuitively and simply recognizes impulse noises, while keeping the others intact as nonnoises. Depending on different noise ratios at an image, two different sets of masked pixels are employed separately for the adoption of candidates for median finding. Furthermore, no limit to the size of mask windows assures that a proper median can be found. The simple logic of the proposed algorithm achieves significant milestones on the fidelity of a restored image. Moreover, the very fast execution speed of the proposed filter is very suitable for being applied to real-time processing. Relevant experimental results on subjective visualization and objective digital measure are reported to validate the robustness of the proposed filter.

1. Introduction

Noise always degrades otherwise normal images as images are transmitted or duplicated from defective transmission channels and devices. The detriment caused usually makes it difficult to know what a completely original image is. Specifically, noises seriously affect the performance of image processing applications, including land cover classification (Gong et al., 2011), ellipse detector (Chia et al., 2011), image watermarking (Nezhadarya et al., 2011), face recognition (Naseem et al., 2012), and many others. Therefore, it is important to get rid of the noises in a corrupted image. In general, the noises in a corrupted image cannot be erased completely, while most of noise removal methods approximate noise-free images to be near original fidelity. Salt-and-pepper is one of the significant impulse noises that may occur in images. Lots of methods have been proposed to eliminate the salt-and-pepper noises in a corrupted image. Median filters are widely thought to be better ones for removing impulse noises since they can also preserve the edges in a corrupted image. The filters can be performed more effectively with the front-end and subsequent processes, such as edge detection, segmentation, classification, and recognition. However, due to the uncertainty of the distribution of the impulse noises, it is difficult to find a mathematical model to analyze and get rid of them.

For the restoration of images corrupted with salt-and-pepper impulse noise, most of the past median filters were designed on the basis of the two passes: noise detection and noise filtering. The logic of each of the two passes is an iterative process like those proposed in Progressive Switching Median Filter (PSMF) (Wang and Zhang, 1999). However, basic passes cannot fully find out all noises and correctly restore images. Besides, it is obvious that the processing procedures consume a lot of time. In the worst case, the quality of the restored image is not satisfactory, especially for the content of higher levels of impulse noise. Fortunately, a series of improved algorithms (Nallaperumal et al., 2006a, 2006b, 2006c, 2007; Varghese, 2007; we found that Varghese (2007) is the combination of Nallaperumal et al. (2007) and Nallaperumal et al. (2006c)) were proposed successively to simplify the process from two passes into one pass, thus reducing much time in logic execution. Although the one-pass concept appears promising, there are still some defects to be improved, especially for images corrupted at noise ratios lower than 30% and higher than 90%. As presented by Cangju (2008), it really obtains a better result by examining its *PSNRs* (Peak Signal to Noise Ratio) that are evident but this process reduces edge quality and blurs the image. The median-finding procedure (Ibrahim et al., 2008) defines that the number of nature pixels must not be less than eight in any adaptive window. Under this condition, candidate neighbors may be far away from the noisy pixel currently processed. This causes more redundant computations to waste processing and the value of the median may be far from the original fidelity. Also, the algorithm presented by Toh et al. (2008) does not use two-pass concept in performing noise detection and median finding. However,

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the use of fuzzy mechanism still implies a risk in exactly checking whether a pixel is really noisy. The idea proposed by Ng and Ma (2006) uses hybrid noise model to detect boundary discriminative noises, but the *PSNRs* it obtains for a specified noise ratio with different proportions of salt-and-pepper noise vary largely. Thus, unstable element is revealed in this approach.

As the statistical operator is the key computation in the median filter, a distinctive sorting method is employed by Kishore and Rao (2008) to accelerate the noise detection. Furthermore, different mask windows are suggested for different noise ratios to reduce redundant computation and to promote performance efficiency (Kishore and Rao, 2008). In order to keep the details of the original image intact, the Detail-Preserving Median Filter (DPMF) is proposed by Li et al. (2009); however, the logic and the execution results are almost the same as those given by Nallaperumal et al. (2006a, 2006b, 2006c) (One of our targets is to overcome this weakness). Similarly, two-pass concept is employed by Toh and Isa (2010) so as to slow down the performance of its complex algorithm without improving the final result. One linear prediction directly regards the impulse values as noises during noise detection (Jayaraj and Ebenezer, 2010), but it cannot accurately find medians compared with those of other techniques. Khan et al. (2010) employed unsharp filter in combination with smoothing operation. It restores contaminated images to be blurred ones; much worse, the higher the noise ratio is, the more blurred the restored image may be. In the course of performing the method, it needs the original image to be retained to be compared with the corrupted image for noise detection. In order to further reduce noise pixels, the two-state switching median filter uses one standard filter and one further filter (Xia et al., 2010). However, the appeal of the concept is also reduced since the image is filtered twice. Besides, the size of the adaptive window W is improperly bounded to be 11, the maximum; this may cause part of noisy pixels to have no nonnoisy median values to replace themselves. Yu et al. (2010) employed probability concept for noise detection, but numerous incorrect detections degrade its performance to yield results more unsatisfactory than many recently proposed filters do.

It is clear that lots of noise detection methods cannot fully and correctly find out all the noises in a corrupted image. On the other hand, inefficient iterative computation always increase the computation cost and the final restored image is still unsatisfactory. Although many methods with *PSNR* digits are presented in even recent published literatures (Jayaraj and Ebenezer, 2010; Huang et al., 2010; Majid and Mahmood, 2010; Majid et al., 2010; Pan et al., 2010; Wang et al., 2010; Patel et al., 2011; Nair and Mol, 2011), the improvement rate is not significant since the outmoded idea is still reused. For the filters based on fuzzy theory (Hussain, 2009, 2010; Masood et al., 2011), the results obtained are common and not very competitive with those of superior filters. This paper proposes a new median filter against the two paradigm algorithms, PSMF (Wang and Zhang, 1999) and Adaptive Rank-ordered Switching Median Filter (ARSMF; Nallaperumal et al., 2006a, 2006b, 2006c). We will show that the adoption of the two parameters (T_C and W_{max} in ARSMF) is sure to be a stumbling block, although these parameters can increase the performance and the quality of recovered images. Fortunately, we have solved the intractability using only simple logic to generate satisfying results at real time. The proposed logic operator directly recognizes the pixels with the smallest value and the highest value as impulse noises. Also, the new median filter keeps nonnoisy pixels intact in the corrupted image, while performing median-filtering procedures to deal with noises for finding proper medians for replacement. There is no redundant logic in noise detection and median-finding processes. Therefore, the execution time of the proposed filter is properly amenable for real-time applications. The concept and the details of the proposed filter are described as Fig. 1 and in below sections.

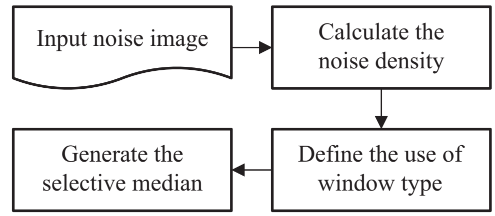

Fig. 1. Flowchart of the proposed method.

2. Proposed filter

Similar to other impulse detection algorithms (Wang and Zhang, 1999; Nallaperumal et al., 2006a, 2006b, 2006c, 2007; Varghese 2007), our impulse filter is developed by prior information on natural images, i.e., a noise-free image should be locally smoothly varying, and is separated by edges. In this paper, we focus on only salt-and-pepper impulsive noise with two significant features described as follows:

1) As a portion of the image pixels is corrupted, other pixels are noise-free.
2) A noise pixel takes either a very large value as a positive impulse or a very small value as a negative impulse.

The hallmark of our proposed Fast and Efficient Median Filter (FEMF) is its excellent performance in the efficiency of accurate result acquisition and execution speed. Furthermore, our FEMF can efficiently restore images corrupted at 1–99% levels of noise ratio, while taking full care to restore only the corrupted pixels through efficient computation. This is accomplished by an adaptive median-finding procedure to find an optimal median for a specified noisy pixel.

Suppose that $I=\{\, f_i=(f_1,\ f_2)|0\le f_1\le M,\ 0\le f_2\le N\}$ represents all the pixels in an image of size M by N. The proposed FEMF uses a set of spatial position denoted by Ω as statistics of prior information. For each pixel, Ω is centered around the pixel at position $i=(i_1,\ i_2)$ within an adaptive window initialized to be of size 3×3. Fig. 1 shows the flowchart of the proposed FEMF.

The quantity analysis of noises can be taken into consideration to evaluate the noise filter producing best results. Adaptive windows of different types are employed for various densities of noise ratio. In median-finding procedures using adaptive windows, the neighbor pixels to the centered noise pixel in a window are employed to adopt a median among them. However, the adoption of an optimal median depends on the number of the neighbor pixels validated as candidates for median finding. For low levels of noise ratio, a small window is adequately used for median finding since noise-free pixels can be easily searched from neighbors. On the other hand, a large one should be employed for the degraded image at high noise ratio. This is because neighbors may not include applicable pixels to each noise pixel. Therefore, we evaluate the noise density as the prior information to the median filter. According to the prior works, the highest and the lowest values are regarded as noise pixels. The density of noise ratio can then be calculated by the numerator corresponding to the integrated number of noisy pixels and the denominator as the digital resolution of the input image.

This paper uses a simplified window and a full window shown in Fig. 2 to deal with various noised images. If only sparse noises exist in the original image, searching the diagonal sides of the window is not necessary, while the applicable pixels qualified to be candidates can be searched from horizontal and vertical lines illustrated in Fig. 2(a). Otherwise, the full window must be employed for the image at high densities of noise ratio to search the rest of pixels, which is shown in Fig. 2(b). The development achieves that for these two kinds of window, not only the execution performance is efficient but also the fidelity of validated candidates

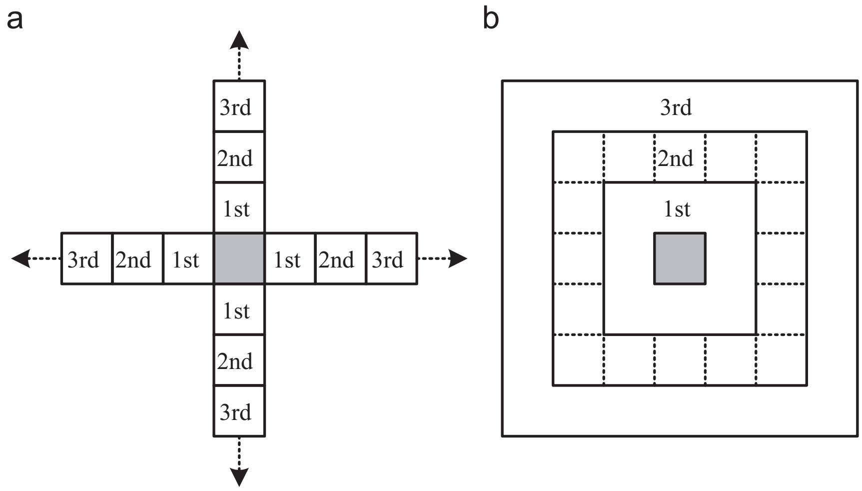

Fig. 2. Employed types of windows; (a) the simplified type for low densities of noise ratio; (b) the full type for high densities of noise ratio.

is near the centered noise pixel. Empirically, the simplified window is utilized as the noise density is less than 50%, whereas the full window is applied for the other noise densities.

With our proposed method, we can easily improve the quality of an input noise image as the type of window is determined on the noise ratio of the input image. The pseudo-code of the proposed median filter is described in Algorithm 1. In the proposed algorithm, the horizontal and vertical arrows are radiated from the position of the centered pixel for the simplified window shown in Fig. 2(a), and two heads of the corresponding arrows are represented by Ω^{sh} and Ω^{sv}, respectively. Similarly, a set composed of all the pixels on the outmost four sides of the full window (Fig. 2(b)) can be formed by Ω^{fh} combined with Ω^{fv}. Once nonnoise pixels are captured from the corresponding set, the median value is calculated to replace the centered noise pixel. Otherwise, the size of the window is adaptively increased until at least one nonnoise pixel is found.

Algorithm 1 The proposed FEMF

Input: noise image I and parameter W
Output: Improved image I'
Initialize W to be 3
Evaluate the noise density E
for $f_2 \leftarrow 0$ to $N-1$ **do**
  for $f_1 \leftarrow 0$ to $M-1$ **do**
    if $E \leq 50\%$ **then**
      $\Omega^{sh}=\{j=(i_1, j_2) \mid j_2=i_2 \pm (W-1)/2\}$
      $\Omega^{sv}=\{j=(j_1, i_2) \mid j_1=i_1 \pm (W-1)/2\}$
      Set S as a set composed of Ω^{sh} and Ω^{sv}
    else
      $\Omega^{fh}=\{j=(j_1, j_2) \mid i_1-(W-1)/2 \leq j_1 \leq i_1+(W-1)/2, j_2=i_2 \pm (W-1)/2\}$
      $\Omega^{fv}=\{j=(j_1, j_2) \mid j_1=i_1 \pm (W-1)/2, i_2-(W-1)/2 \leq j_2 \leq i_2+(W-1)/2\}$
      Set S as a set composed of Ω^{fh} and Ω^{fv}
    end if
    if S does not include noise-free pixels **then**
      $W=W+2$ and go to line 7
    else
      Set H as a set of noise-free pixels in S
      $f_i'=\text{median}(H)$
    end if
  end for
end for

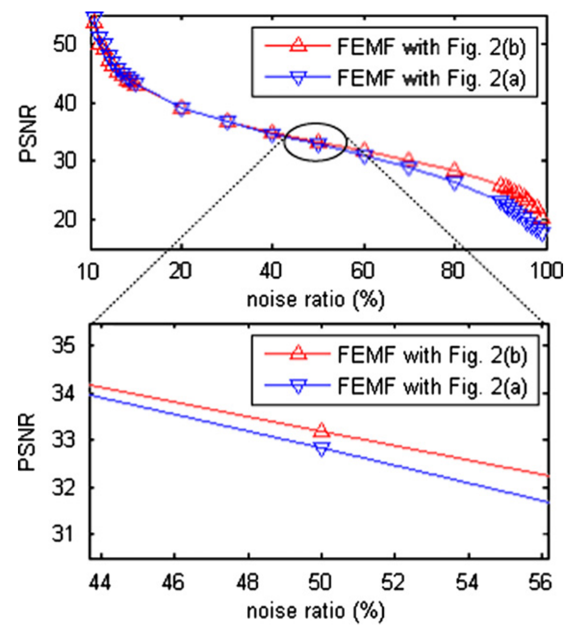

Fig. 3. Estimated *PSNRs* of the proposed method using different types of windows.

3. Experimental results

Against PSMF and ARSMF, the performance of the proposed algorithm has been tested on several standard 512×512 images, Lena, Girlface, Boat, and Pepper, of which, Lena was taken to be used for our subjective and objective analysis. In the mean time, we also make some comparisons between our results and those of PSMF and ARSMF. The objective standard of the performance of these median filters is the *PSNR* of the restored images previously corrupted at various levels of noise ratio. With respect to the noise-free image A, the definition of *PSNR* for a final restored image Z sized $M \times N$ is

$$PSNR = 10\log_{10}\frac{255^2}{MSE} \tag{1}$$

where *MSE* is defined as

$$MSE = \frac{\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}(A(x,y)-Z(x,y))^2}{MN} \tag{2}$$

3.1. Analysis of FEMF

Applying the first type of window (Fig. 2(a)) and the second type of window (Fig. 2(b)) separately to the FEMF for corrupted Lena images, we can obtain the results illustrated in Fig. 3. In Fig. 3, we can find that for images corrupted at 0–40% of noise ratio, the *PSNR* values of the method using the first type of window are better than those of that using the second type of window; meanwhile, the same nature appears for execution speeds. On the contrary, for the *PSNR* values and execution speeds for higher levels (60–99%) of noise ratio, the method using the first type of window is poorer than that using the second type of window. Naturally, in Fig. 3, the superior parts of the comparison between the results from the two methods are the parts we favor. In Fig. 3, the performance of the method using the second type of window has been competitive enough with those of other papers; furthermore, the performance of the method using the first type of window is superior to that of the method using the second type of window for the noise ratios below mid level. In other words, we can regard the method using the first type of window as the improved version of the method using the second type of window for low levels of noise ratio.

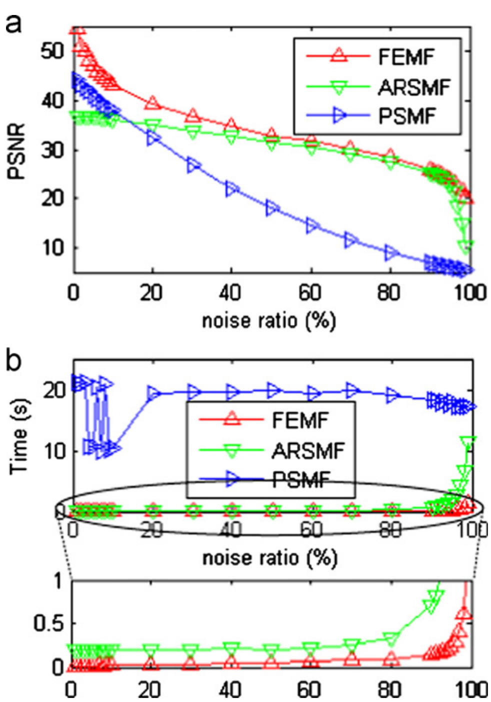

Fig. 4. Comparison of noise reduction methods for (a) quantitative measurement and (b) execution time.

3.2. Quantitative measurement and performance estimation

The superior results of the two methods described previously make FEMF's integrated results more competitive, which is shown in Fig. 4. Therefore, we declare that the integration of the two methods proposed above constructs our proposed algorithm, i.e., we use simplified windows to process the images corrupted at 0–50% of noise ratio and full windows to process the images corrupted at 51–99% of noise ratio. Here, we use 50% of noise ratio to be the boundary line to determine when to apply which of these two methods. In fact, the digit 50% comes rationally after our lots of experiments and analysis on different kinds of images (Lena, Girlface, Boat, Pepper, etc.). We learn that the *PSNR* values produced by the two methods for 40–60% of noise ratio vary a little (generally speaking, less than 0.5 of *PSNR* value). To reduce the complexity of the adoption of the boundary line for noise ratio, we suggest that 50% of noise ratio be used as the boundary line.

Presented in Fig. 4, the real difference between FEMF and the other two is obviously discovered. In Fig. 4, we can see that the *PSNR* values strongly illustrate the advantage of the proposed filter at 1–99% levels of noise ratio. Moreover, the *PSNR* values by FEMF are even far better than those of most filters so far proposed.

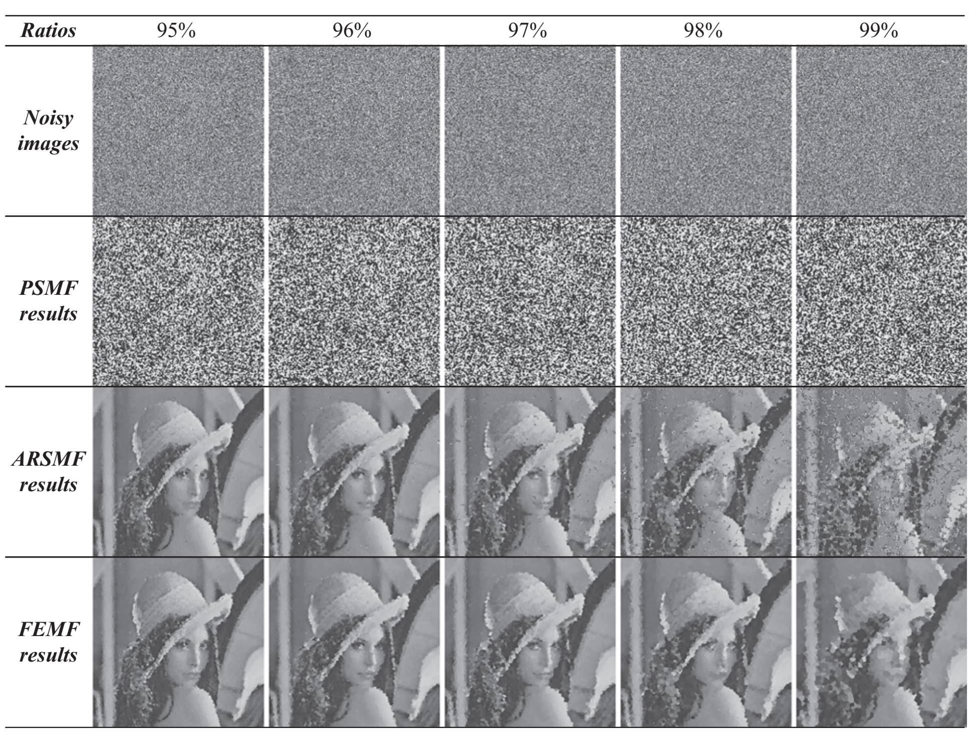

Fig. 5. Noise reduction by each method for Lena images at different noise ratios.

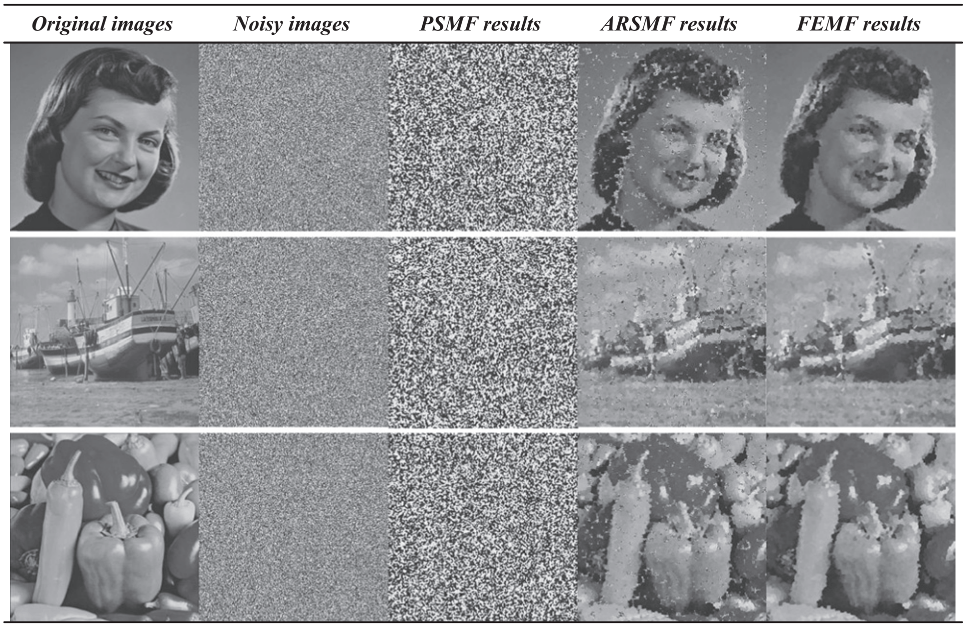

Fig. 6. Noise reduction by each method for different gray-scale images at 98% of noise ratio.

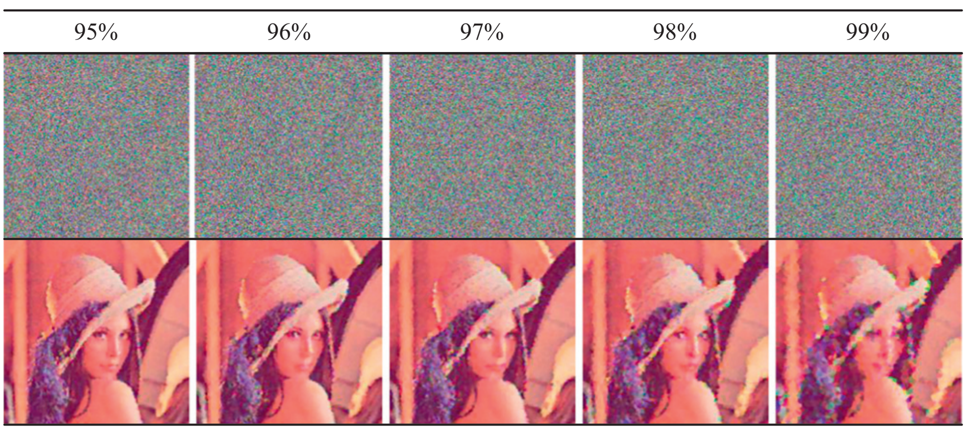

Fig. 7. Noise reduction by the proposed method for color images at different noise ratios.

3.3. Qualitative Evaluation

In Fig. 5, due to the extreme high rate of noise mis-detection, the results generated by PSMF are highly unsatisfactory and we cannot even realize what the original images corresponding to the corrupted ones look like. As for ARSMF, image distortion is getting to form for the restored image from that corrupted at 95% of noise ratio. For the restored image from that corrupted at 99% of noise ratio, at least one third of the image space is spread over with noises. The main reason is that the stumbling blocks, T_C and W_{max} values, are invited to work with ARSMF so that it keeps noises as medians when no medians are found at high levels of noise ratio. Conversely, our proposed filter follows natural and adaptive way and is able to find a proper median for each noise pixel without miss. Therefore, even the restored image from that corrupted at 99% of noise ratio is still visually distinguishable. In order to check if our proposed filter is amenable, we adopt another three images, Girlface, Boat and Pepper shown in Fig. 6, different from Lena in brightness to test and check the results obtained. Excitingly, these results in Fig. 6 illustrate that the images restored from those corrupted at 98% of noise ratio are satisfactory. This really explains the superiority of our proposed filter.

In addition, with the rapid development of image technology, color images are now wildly accepted. Thus, we also employ our proposed filter during the restoration of corrupted color images. In similarity, satisfactory restored results shown in Fig. 7 again strongly support the robustness of our proposed filter, FEMF.

With the visual demonstration of Figs. 5–7, we can realize the superiority of our proposed filter in removal of noises in corrupted images. The competitive results by FEMF having been compared with those of most papers published, our proposed filter really outperforms most of the filters so far proposed, not to mention the earlier PSMF and ARSMF.

Actually, salt-and-pepper is a specialized case for impulse noises. In order to increase the convenience of simulation, the related literatures (Ibrahim et al., 2008; Toh et al., 2008; Ng and Ma, 2006; Kishore and Rao, 2008; Li et al., 2009; Jayaraj and Ebenezer, 2010; Yu et al., 2010; Majid and Mahmood, 2010; Majid et al., 2010; Wang et al., 2010; Nair and Mol, 2011) all set the lowest and the highest values as noises and similarly this paper also follows this setting in experiments. However, if original images include large areas of the lowest or the highest value, this setting will be failed. Therefore, the median filter can be integrated with the efficient impulse noise detection algorithm to further the performance.

4. Conclusion

FEMF's performance really reveals its superiority in subjective visualization and objective digital measure. Without any miss, the proposed filter FEMF directly recognizes the lowest and the highest values as low and high noises. Moreover, without retaining any noise in the restored image, a robust integrated noise-filtering procedure of FEMF is devised to be absolute and accurate in finding proper medians to replace related noises. The competitive *PSNR* values produced by FEMF prove its nice nature. The remarkable performances for the execution time of FEMF are convincing to declare that FEMF is a potential candidate filter for real-time processing. Thanks to the simplicity in structure and the better performance of FEMF, it can really be regarded as a general-purposed median filter for removing salt-and-pepper noises in varieties of both gray and color images corrupted at 1–99% levels of noise ratio.

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