Random-valued Impulse Noise Reduction in Color Image by Using Switching Vector Median Filter with MST-based Noise Detector

Takanori Koga and Noriaki Suetake

Abstract—**This paper describes the noise reduction performance of a switching vector median filter with a random-valued impulse noise detector for color images. As a random-valued impulse noise detector, a minimum spanning tree (MST)-based method is employed. In the switching vector median filter, the impulse noise detector is employed before filtering, and the detection result is used to judge whether a pixel should be filtered or not. By applying the method to color images, it is expected that the random-valued impulse noise is reduced pointedly while preserving detailed structures such as thin line, sharp corner, and so on. Through some experiments, for color images, the effectiveness of the combination of the switching vector median filter with the MST-based random-valued impulse noise detector is verified. Particularly, the present method is compared to some powerful switching vector median filters which had been proposed so far from a view point that the impulse noise reduction while preserving edges and details of an image is realized or not.**

Index Terms—**image denoising, impulse noise detector, random-valued impulse noise, minimum spanning tree, switching vector median filter.**

I. Introduction

COLOR images, especially treated in embedded equipments, are corrupted frequently by noises due to degrading factors such as defection of image sensor, thermal noise from electric circuits around the image sensor, deterioration of data storage, and data transfer error and so on [1]. Particularly, impulse noise is generated by bit error in the data transfer process, and may be typically defined as the corruption which has randomness and sparseness, and is high or low amplitude relative to local pixel values. In the impulse noise reduction, it is generally important to suppress the noise while preserving the integrity of edge and detail information.

In order to realize detail-preserving impulse noise reduction, a switching median filter is used frequently. In the switching median filter, an impulse noise detector previously detects pixels to be processed. Then the detected pixels are processed by the median filter. The conventional impulse noise detector can detect the salt-and-pepper noise relatively well [2], [3]. However, detailed structures such as thin line and corner of edge in an input image to be fed to filter are wrongly regarded as noises by the detector. Thus those structures are ruined in median filtering process. This ruin of the structures due to misdetection of noises is unavoidable fundamentally. This is because the noise detector uses the output image of the median filter in the noise detection process. Furthermore, it can be said that the conventional detector is not also suitable for the detection of the random-valued impulse noise which has similar amplitude to values of neighboring pixels.

On the other hand, an impulse noise detector which does not tend to misdetect the detailed-structures as noises had been proposed [4]. This detector employs a minimum spanning tree (MST) of graph theory [5] for noise detection. By using MST-based detector, it had been verified that the random-valued impulse noise elimination and the detail-preserving filtering had been achieved with a perfect balance for gray-scaled images. However, the performances of the MST-based noise detector for color images have not been proved yet.

In this paper, the performance of the combination of random-valued impulse noise detection algorithm with MST [4] and a switching vector median filter (SVMF) for color image is evaluated. In the present method, the MST based on the Euclidian distance among neighboring pixels is employed to estimate probability of being noise-corrupted pixel. After that, the SVMF is applied selectively to remove the random-valued impulse noises. The SVMF is able to achieve median filtering in color image without color shift.

The effectiveness of the present algorithm for color image is verified quantitatively and qualitatively by some experiments using an artificial image and natural images.

II. Noise Detection and Filtering Process

In this section, the model of random-valued impulse noise and the proposed method are described.

A. Noise Model

Here, let $\boldsymbol{I}(x,y)$ be a vectorized pixel value of an input color image with 8-bit in R, G, and B channels. In this study, suppose that the random-valued impulse noise model as follows:

$$\boldsymbol{I}(x,y)=\begin{cases}(I_R,I_G,I_B) & 1-p_R-p_G-p_B\\(d,I_G,I_B) & p_R\\(I_R,d,I_B) & p_G\\(I_R,I_G,d) & p_B,\end{cases} \tag{1}$$

$$p=p_R=p_G=p_B, \tag{2}$$

where d represents the value of impulse noise. Note that the coordinates (x,y) are omitted in the right side. Supposing

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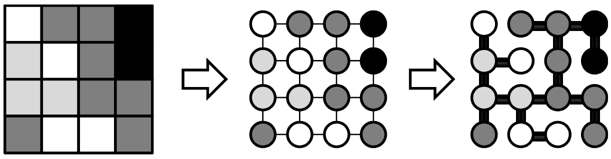

Fig. 1. MST of a graph obtained from an image.

that bit error can occur with equal probability for all bits, the value of d is given by uniform random numbers ranged from 0 to 255. I_R, I_G, and I_B are pixel values correspond to R, G, and B channels of the noise-free original image, respectively. The impulse noise is replaced with equal probability p for each channel.

B. Minimum Spanning Tree (MST) by Kruskal's Greedy Algorithm

Let $G = (V, E, W)$ be a connected graph. Here V, E, and W are a set of vertices, that of edges, and that of edge weights, respectively. Each edge $(u, v) \in E$ has an associated weight $w(u, v)$. Here, by regarding each pixel in an input image as a vertex, the graph associated with the input image is constructed. In this regard, edges exist exclusively between a pixel and its neighboring pixel on the left, right, top and bottom. In this study, the edge weight between pixels at (x_1, y_1) and at (x_2, y_2) is given by $\| \boldsymbol{I}(x_1, y_1) - \boldsymbol{I}(x_2, y_2) \|$. Under such definition, a spanning tree for G is a subgraph of G that is a tree connecting all vertices in V. The weight of a spanning tree is the sum of weights on its edges. A minimum spanning tree (MST) of G has the minimum weight. The Kruskal's greedy algorithm [6], which is a MST finding algorithm, is used here. The process is explained briefly as follows:

Let a state be a set of edges $S(\subset E)$. In the initial state, $S = \emptyset$.

Step 1 : Make a queue E in ascending weight by using sorting algorithm such as merge sort.

Step 2 : While $E \neq \emptyset$, the condition, "$S \cup \{e\}$ does not contain any cycle," is verified for the head edge e in the queue E. If the condition is satisfied, the state and the queue are updated as follows: $S \leftarrow S \cup \{e\}$, $E \leftarrow E - \{e\}$. Otherwise, the state is not updated and the queue is updated as follows: $S \leftarrow S$, $E \leftarrow E - \{e\}$. If the queue is empty, the state S represents the MST.

An example of an MST of a graph obtained from a gray-scaled image is shown in Fig.1. If there are edges with the same weight, theoretically, the MST may not be constructed uniquely. In this case, note that the edge found in first among them in a raster order in the input image is queued in line on ahead.

C. Impulse Noise Detector Using MST

In the present method, a partial image corresponding to a local region of an input image is expressed as a graph, and then its MST is constructed by using the Kruskal's greedy algorithm. In the MST, the end-vertex, which is a vertex connected to another vertex by unique edge, tends to be a pixel corrupted by the random-valued impulse noise. In the

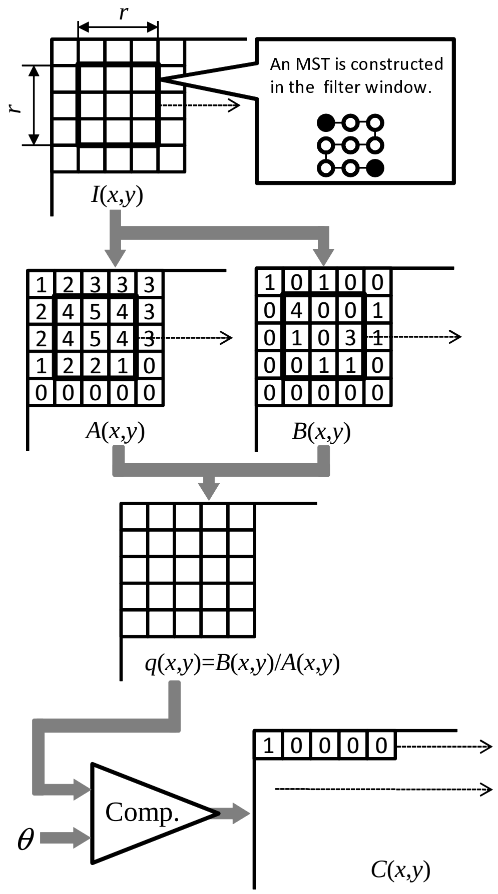

Fig. 2. Schematic of the procedures to obtain the noise map.

MST-based detector, by using this characteristic, random-valued impulse noises are detected [4] by the following procedures (see Fig.2):

Step 1 : Arrange zero matrices $A(x, y)$ and $B(x, y)$ as counters which have the same size to the input image. Start the following process from the upper left of the input image. $A(x, y)$ stores the processed times by the MST-based detector for each pixel, and $B(x, y)$ stores detected times as the end-vertex for each pixel.

Step 2 : Increment values of counter matrix $A(x, y)$ corresponding to all pixels within the local processing window which has $r \times r$ pixels.

Step 3 : Create a MST of a graph expressed by using the partial image consisting of pixels in the local processing window, and increment values of counter matrix $B(x, y)$ corresponding to all end-vertices in the MST.

Step 4 : Repeat **Step 2** and **Step 3** in a raster order for the input image.

Step 5 : Calculate all pixels' probabilities of being noise $q(x, y) = B(x, y)/A(x, y)$.

Step 6 : Create a zero matrix $C(x, y)$ which has the same size to the input image as a noise map. If $q(x, y)$ is larger than or equal to a threshold θ, then set $C(x, y)$ to 1. This means that $\boldsymbol{I}(x, y)$ is corrupted by the random-valued impulse noise. Otherwise, $\boldsymbol{I}(x, y)$ is a noise-free pixel.

In the MST-based detection algorithm, it can be said that the pixel, whose value is stood out in comparison with those of neighboring pixels, can be detected as the noisy pixel independently of the amplitude of the noise. Furthermore, pixels constituting line structures tend to be not detected as noises because edges of the MST creep on the line structures and thus noise probabilities of them are dispersed, and become small.

D. Switching Vector Median Filter

Here, let a filter window size, a multi-channel signal in the filter window, and a distance between vector $\boldsymbol{I}_i$ and $\boldsymbol{I}_j$ be $n+1$, $\boldsymbol{I}_j (j = 0, 1, ..., n)$, and $\eta(\boldsymbol{I}_i, \boldsymbol{I}_j)$, respectively. A scalar R_i is obtained as follows:

$$R_i = \sum_{j=0}^{n} \eta(\boldsymbol{I}_i, \boldsymbol{I}_j). \tag{3}$$

This equation represents a sum of the distance between an arbitrary vector $\boldsymbol{I}_i$ and the other vector $\boldsymbol{I}_j$ in the filter window.

By letting R_i arrange in ascending order as $R_{(0)} \leq R_{(1)} \leq \cdots \leq R_{(n)}$, and letting $\boldsymbol{I}_{(i)}$ be the corresponding multi-channel (vector) signal to $R_{(i)}$, the ordering of the multi-channel signal is represented as $\boldsymbol{I}_{(0)} \leq \boldsymbol{I}_{(1)} \leq \cdots \leq \boldsymbol{I}_{(n)}$.

The output of vector median filter (VMF) $\boldsymbol{I}^*$ satisfies the following condition.

$$\sum_{j=0}^{n} \eta(\boldsymbol{I}^*, \boldsymbol{I}_j) \leq \sum_{j=0}^{n} \eta(\boldsymbol{I}_i, \boldsymbol{I}_j), \quad i = 0, ..., n, \tag{4}$$

where $\eta(\cdot)$ represents L1 norm. Thus, the output of VMF is a vector which makes the sum of distance for the other vectors in the filter window minimum.

In the switching vector median filter (SVMF), by employing pre-obtained noise map $C(x, y)$, an output $\boldsymbol{I}'(x, y)$ is given as follows:

$$\boldsymbol{I}'(x, y) = \begin{cases} \boldsymbol{I}^*(x, y) & C(x, y) = 1 \\ \boldsymbol{I}(x, y) & \text{otherwise.} \end{cases} \tag{5}$$

The SVMF can perform median filtering in color image without color shift.

III. Experiments and Results

At first, in the experiment, noise reduction for a simple artificial color image is performed in order to show obviously the fact that the proposed SVMF with MST-based noise detector can preserve the thin lines and corners compared to other methods. Then natural images of the standard image database (SIDBA) are used for evaluation of the proposed method in practical situation.

In each experiment, the mixing rate of the random-valued impulse noise p is set to be from 0.01 to 0.03 by considering practical situation.

A. Test for Artificial Image

A test image is generated artificially, and is then applied to the vector median filter (VMF), to Sun's switching median filter (SSMF) [2], to the robust switching vector median filter (RSVM) [7], and to the proposed switching vector median filter with MST-based noise detector (SVMF-MST). Figure 3(a) shows a color image (65×65 pixels, 8 bit/pixel for each RGB channel) including line structures for testing. The lines have width of 1 pixel. In the image, the colors of the line parts are generated from combinations of brightness

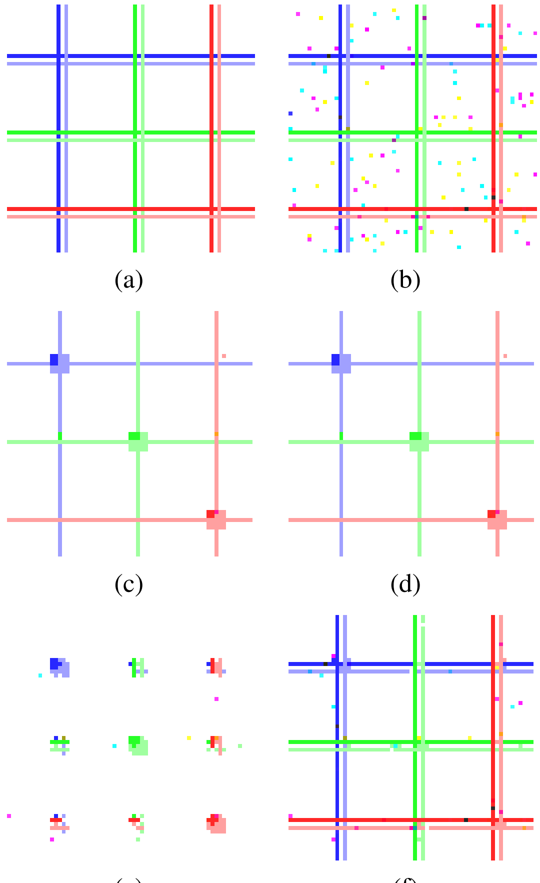

Fig. 3. Filtering results for an artificially-generated test image containing line structures. (a) Original image. (b) Noise-corrupted image with $p = 0.01$. (c) VMF ($r = 3$), (d) SSMF ($r = 3$). (e) RSVM ($r = 3$). (f) SVMF-MST ($r = 3$, $\theta = 0.7$).

TABLE I
MSE OF FILTERING RESULTS FOR AN ARTIFICIALLY-GENERATED TEST IMAGE CONTAINING LINE STRUCTURES.

	$p=0.01$	$p=0.02$	$p=0.03$
Corrupted image	1435.7	2695.8	4024.5
VMF	8263.9	8240.7	8263.9
SSMF	8277.6	8253.2	8268.0
RSVM	7260.8	7123.1	6930.3
SVMF-MST	378.6	495.1	1146.5

TABLE II
NDA OF FILTERING RESULTS FOR AN ARTIFICIALLY-GENERATED TEST IMAGE CONTAINING LINE STRUCTURES.

	$p=0.01$	$p=0.02$	$p=0.03$
SSMF	95.7%	98.3%	99.4%
RSVM	100.0%	97.4%	96.8%
SVMF-MST	89.7%	88.5%	79.9%

TABLE III
NDE OF FILTERING RESULTS FOR AN ARTIFICIALLY-GENERATED TEST IMAGE CONTAINING LINE STRUCTURES.

	$p=0.01$	$p=0.02$	$p=0.03$
SSMF	89.8%	80.6%	73.2%
RSVM	95.7%	90.2%	84.2%
SVMF-MST	12.5%	4.1%	6.1%

values {40, 160} for each channel. Figure 3(b) shows a noisy test image corrupted by random-valued impulse noise with $p = 0.01$. Figures 3(c), 3(d), 3(e), and 3(f) show the filtering results by VMF, SSMF, RSVM, and SVMF-MST, respectively. The threshold value of SSMF is given by the following equation [8], $\Theta = 0.314P^2 - 5.94P + 57.7$. Here, P represents the percentage of noise generation probability. The parameter α of RSVM is set to be 1.25 [7]. θ of SVMF-MST is experimentally set to be 0.7 that gives the best performance concerning a mean square error (MSE) in this case. Sizes of filtering window are 3×3 ($r=3$) pixels in all methods.

From Figs.3(c), 3(d), and 3(e) it can be seen that VMF, SSMF and RSVM cannot preserve line structures in the image. By changing the threshold value, it can preserve line structures. However, in this case, many impulse noises are not detected, and are not removed well. On the other hand, in the proposed SVMF-MST, the superior result is obtained in comparison with the others, as shown in Fig.3(f). However, some impulse noises remained on the lines and beside the lines, moreover, some artifacts are observed in the cross points of lines in this case.

Tables I, II and III show the MSE, the noise detection ability (NDA) and the noise detection error (NDE), respectively. The test image is corrupted by the random-valued impulse noise with $p = 0.01$, 0.02, and 0.03. The MSE is calculated by the following equation:

$$MSE = \frac{1}{M \times M'} \sum_{x=1}^{M} \sum_{y=1}^{M'} \| \boldsymbol{I}(x, y) - \boldsymbol{I}'(x, y) \|^2, \quad (6)$$

where M and M' represent the number of pixel in row and in column, respectively.

The NDA is calculated by the following equation:

$$NDA = \frac{N_{collect}}{N_{noise}} \times 100(\%), \quad (7)$$

where $N_{collect}$ and N_{noise} stand for the number of correctly-detected noise and that of noise-corrupted pixel, respectively.

The NDE is calculated by the following equation:

$$NDE = (1.0 - \frac{N_{collect}}{N_{total}}) \times 100(\%), \quad (8)$$

where N_{total} stand for the total number of noise-corrupted pixel.

The results show that the proposed method has superior noise detection ability, and its noise detection error is fewer than that of the others.

B. Test for Natural Image

In the experiments using natural images, “Parrots,” “Mandrill,” “Lenna” and “Airplane” are selected from the standard image database (SIDBA). All the images have detailed structures such as thin line, character, and so on. The test images have 256×256 pixels with 8 bit/pixel for each RGB channel. Those images are applied to the vector median filter (VMF), to Sun’s switching median filter (SSMF) [2], to the robust switching vector median filter (RSVM) [7], and to the proposed switching vector median filter with MST-based noise detector (SVMF-MST). In all experiments, the size of filter window is also 3×3 ($r=3$) pixels. In SSMF and RSVM, the parameters Θ [8] and α [7] are set to be the values

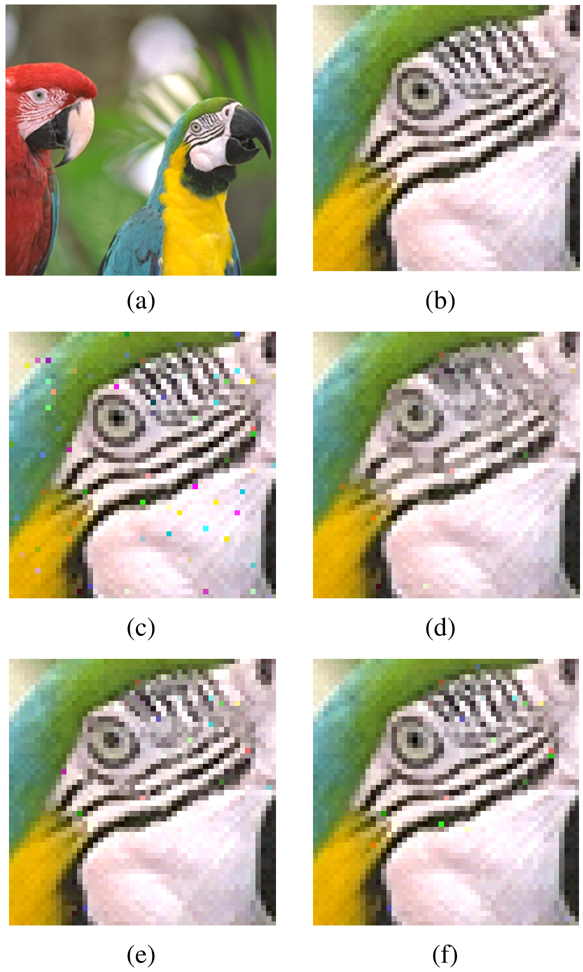

Fig. 4. Natural test image “Parrots” of SIDBA and its filtering results. (a) Original image. (b) Partially-magnified image with line structures. (c) Noise-corrupted image with $p = 0.01$. (d) SSMF ($r=3$). (e) RSVM ($r=3$). (f) SVMF-MST ($r=3$, $\theta=0.7$).

mentioned above. And θ giving best MSE is also employed in SVMF-MST.

Figures 4(a), 4(b), and 4(c) show a whole image of “Parrots,” its magnified partial image including line structures, and a noisy input image corrupted by the random-valued impulse noise with $p=0.01$, respectively. Figures 4(d), 4(e), and 4(f) show filtering results by SSMF, RSVM and SVMF-MST, respectively.

From Fig.4(d), it is observed that the black-and-white zebra-patterned thin line structures around the eye are completely ruined by SSMF, and a few conspicuous noises are still remained. And from Fig.4(e), it is observed that a part of line structure is ruined slightly and is still better than the result of SSMF. Those results are caused by the misdetection in the impulse noise detector. On the other hand, as shown in Fig.4(f), it can be said that SVMF-MST performs the random-valued impulse noise reduction well while preserving edges and details though a few conspicuous noises are still remained.

Table IV shows MSE of filtering results concerning “Parrots” corrupted by the random-valued impulse noise with $p=0.01$, 0.02, and 0.03. From Table IV, it is observed that SVMF-MST is the best in all cases experimented here.

Figures 5(a), 5(b), and 5(c) show a whole image of “Mandrill,” its magnified partial image including sensitive

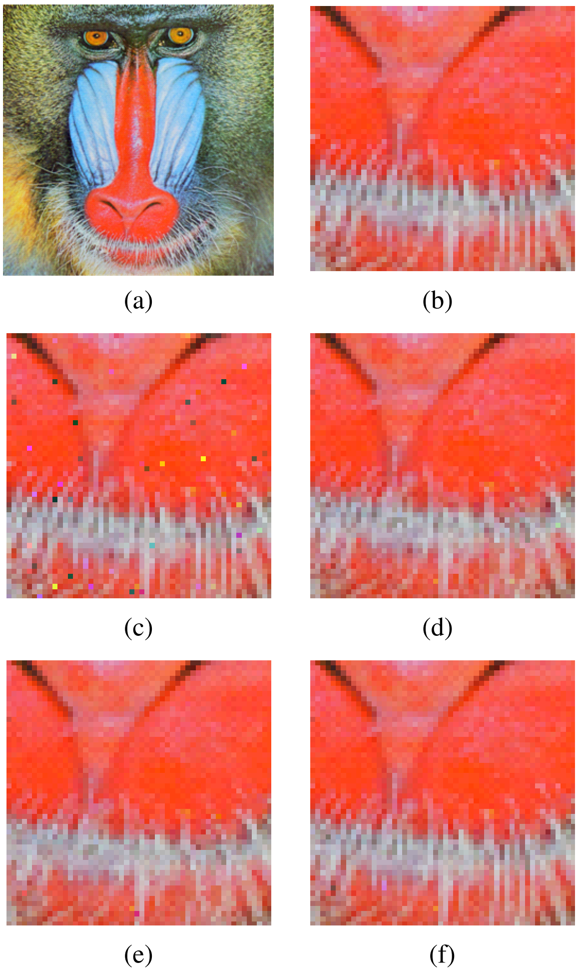

Fig. 5. Natural test image "Mandrill" of SIDBA and its filtering results. (a) Original image. (b) Partially-magnified image with line structures. (c) Noise-corrupted image with $p = 0.01$. (d) SSMF ($r = 3$). (e) RSVM ($r = 3$). (f) SVMF-MST ($r = 3$, $\theta = 0.7$).

Fig. 6. Natural test image "Lenna" of SIDBA and its filtering results. (a) Original image. (b) Partially-magnified image with line structures. (c) Noise-corrupted image with $p = 0.01$. (d) SSMF ($r = 3$). (e) RSVM ($r = 3$). (f) SVMF-MST ($r = 3$, $\theta = 0.7$).

line structures, and a noisy input image corrupted by the random-valued impulse noise with $p = 0.01$, respectively. Figures 5(d), 5(e), and 5(f) show filtering results by SSMF, RSVM and SVMF-MST, respectively.

From Fig.5(d) and (e), it is observed that the faint and sensitive line structures of whiskers are not preserved at all, though the noises are removed almost perfectly by SSMF and RSVM. Those are also caused by the misdetection in the impulse noise detector. On the other hand, as shown in Fig.5(f), it can be said that SVMF-MST performs the random-valued impulse noise reduction well while preserving the faint and sensitive structures of whiskers.

Table V shows MSE of filtering results concerning "Mandrill" corrupted by the random-valued impulse noise with $p = 0.01$, 0.02, and 0.03. From Table V, it is observed that SVMF-MST is the best in all cases experimented here.

Figures 6(a), 6(b), and 6(c) show a whole image of "Lenna," its magnified partial image including line structures such as hair and charm of the hat, and a noisy input image corrupted by the random-valued impulse noise with $p = 0.01$, respectively. Figures 6(d), 6(e), and 6(f) show filtering results by SSMF, RSVM and SVMF-MST, respectively.

From Fig.6(d), it is observed that line structures are somewhat preserved, though the noises are removed almost perfectly by SSMF. This result is much better than the results in case of "Parrots" and "Mandrill." On the other hand, in case of RSVM, it is observed that a part of line structure is ruined appreciably from Fig.6(e). In case of the proposed SVMF-MST, as shown in Fig.6(f), it can be said that SVMF-MST performs the impulse noise reduction well while preserving edges and details though a few conspicuous noises are still remained.

Table VI shows MSEs of filtering results concerning "Lenna" corrupted by the random-valued impulse noise with $p = 0.01$, 0.02, and 0.03. From Table VI, it is observed that SVMF-MST is the best in all cases experimented here.

Figures 7(a), 7(b), and 7(c) show a whole image of "Airplane," its magnified partial image including some characters, and a noisy input image corrupted by the random-valued impulse noise with $p = 0.01$, respectively. Figures 7(d), 7(e), and 7(f) show filtering results by SSMF, RSVM and SVMF-MST, respectively.

From Fig.7(d), it is observed that characters of "F-16" are not preserved, though the noises are well-removed by SSMF. And from Fig.7(e), it is observed that a part of characters is ruined obviously. On the other hand, as shown in Fig.7(f), it can be said that SVMF-MST performs the impulse noise reduction well while preserving the details of the characters.

Table VII shows MSEs of filtering results concerning "Airplane" corrupted by the random-valued impulse noise

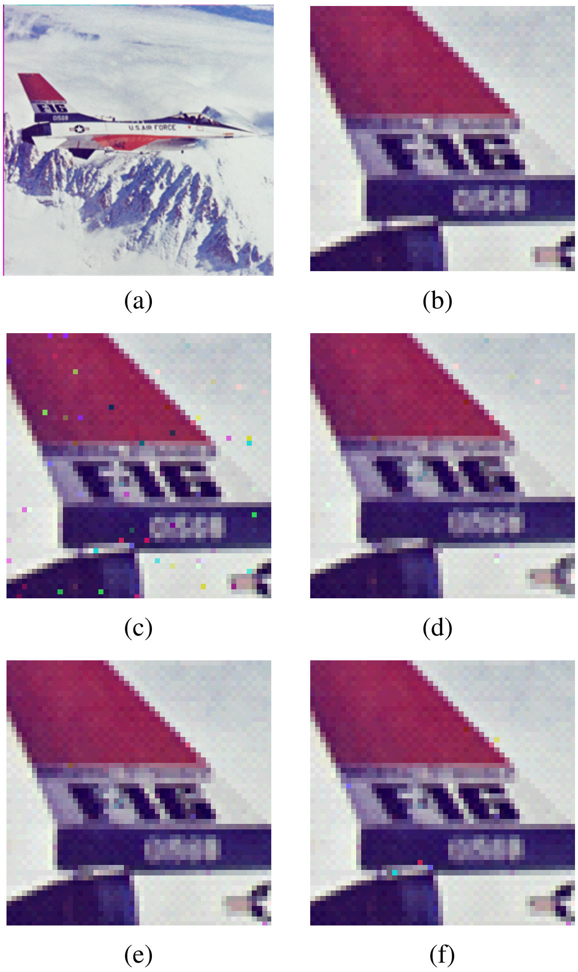

Fig. 7. Natural test image “Airplane” of SIDBA and its filtering results. (a) Original image. (b) Partially-magnified image with characters. (c) Noise-corrupted image with $p = 0.01$. (d) SSMF ($r = 3$). (e) RSVM ($r = 3$). (f) SVMF-MST ($r = 3$, $\theta = 0.7$).

TABLE IV
MSE OF FILTERING RESULTS CONCERNING “PARROTS” CORRUPTED BY RANDOM-VALUED IMPULSE NOISE.

	$p = 0.01$	$p = 0.02$	$p = 0.03$
Corrupted image	279.5	560.0	842.7
SSMF	117.5	140.2	151.8
RSVM	80.8	91.5	98.0
SVMF-MST	39.5	59.2	87.8

TABLE V
MSE OF FILTERING RESULTS CONCERNING “MANDRILL” CORRUPTED BY RANDOM-VALUED IMPULSE NOISE.

	$p = 0.01$	$p = 0.02$	$p = 0.03$
Corrupted image	241.3	493.6	747.1
SSMF	237.4	320.3	401.8
RSVM	366.0	380.3	402.8
SVMF-MST	190.6	221.8	257.2

with $p = 0.01$, 0.02, and 0.03. From Table VII, it is observed that SVMF-MST is the best in most cases experimented here.

By those experimental results using the natural test images, the detail-preserving performance and noise reduction performance of the proposed SVMF-MST was verified.

IV. CONCLUSIONS

In this paper, a combination of the random-valued impulse noise detector based on the minimum spanning tree in graph theory and the switching vector median filter were applied to random-valued impulse noise reduction problem in color image. The distinctive feature of the present method is to be able to reduce pointedly the random-valued impulse noise while preserving edges, line structures, and details in an input image. Through some experiments, the effectiveness and the validity of the present method have been verified.

A future work is to develop an automatic parameter-adjusting algorithm that can determine values of parameters appropriately for each input image of concern. Furthermore, it is very important to improve the noise reduction performance in images corrupted by the random-valued impulse noise with high noise mixing rate.

TABLE VI
MSE OF FILTERING RESULTS CONCERNING “LENNA” CORRUPTED BY RANDOM-VALUED IMPULSE NOISE.

	$p = 0.01$	$p = 0.02$	$p = 0.03$
Corrupted image	261.0	538.7	794.6
SSMF	33.6	50.2	64.7
RSVM	46.5	57.3	67.0
SVMF-MST	26.0	46.0	64.6

TABLE VII
MSE OF FILTERING RESULTS CONCERNING “AIRPLANE” CORRUPTED BY RANDOM-VALUED IMPULSE NOISE.

	$p = 0.01$	$p = 0.02$	$p = 0.03$
Corrupted image	297.6	615.8	921.4
SSMF	81.0	105.6	126.3
RSVM	79.5	90.5	106.7
SVMF-MST	47.9	66.8	107.0

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