ORDER-STATISTIC FILTERS IN DYNAMIC IMAGE SEQUENCES

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Abstract

This paper is concerned with filtering methods in dynamic image sequences corrupted by impulsive noise. Spatial filters based on order statistics are well known. However, image sequences can be considered as spatiotemporal data, that is a time sequence of two-dimensional (2D) images. Thus, in many applications temporal or spatiotemporal filters achieve well performance of noise suppression. Impulse detector can improve the obtained results. Two new spatiotemporal structures of SDV detector are introduced. The analysis of various filtering methods is presented. The performance of the proposed methods is evaluated through subjective and objective criteria, and a new objective criterion was developed.

Keywords

dynamic sequences, impulse noise, order-statistic filter, criterion, correlation, median, LUM filters, temporal, spatial, spatiotemporal filters, detector

1. Introduction

A problem of dynamic image sequences [3,4,6,11] corrupted by the impulsive noise is well known. The median filter is the most widely used in the noise removing and smoothing applications. However, image sequences can be considered as spatiotemporal data, that is a time sequence of two-dimensional (2D) images. In sequences with a little motion the spatial filters based on spatial correlation introduce blurring.

By the exploitation of the temporal and the spatiotemporal correlation, the reduced blurring was achieved. In this paper is presented a number of temporal and spatiotemporal filters. These techniques in connection with some spatial filters are introduced in Section 2.

In many of noise removing applications were acquired better results by the use of impulse detectors. In Section 3 the robust spatial SDV detector and its two spatiotemporal modifications are presented.

In the next section, noise models and the objective criteria are described. The new criterion was developed and introduced.

Experimental results are presented in the Section 5, the pictures and tables are included. Properties of the methods are summarised in the conclusion, where the directions of next research are mentioned.

2. Filter Definitions

For image processing of spatiotemporal data, i.e. dynamic image sequence is appropriate to use temporal and spatiotemporal filters. Thus, it is reduced blurring, that is introduced by some spatial filter structure. The spatial filter is referred to spatial correlation while the temporal filter utilises temporal correlation, only. The spatiotemporal filter is a combination of the spatial and the temporal filter. Thus, it is utilised spatiotemporal correlation, i.e. the temporal correlation of the frames and the spatial correlation within the processed frame.

2.1 Spatial Filters

Nonlinear filters based on order statistics have excellent robustness properties. The best-known order statistic filter is a simple median [1,12] of the points within a filter window.

The output of median filter is given by

$$y^{*} = med\{W\} = x_{((N+1)/2)}, \qquad (1)$$

where y^* is an estimate of the processed sample x^*, W is a set of observations determined by the filter window, $x_{((N+1)/2)}$ is a central sample of ordered set. Note, that W is a set of N samples centered about the sample x^* and *med* is a median operator.

In many applications, the median introduces too much smoothing. The LUM smoother, a subclass of a lower-upper-middle (LUM) filters [2,12,13], achieves the best balance between noise smoothing and signal-detail preservation. A structure of LUM smoother is based on tuning parameter k for the smoothing. Varying this parameter changes the level of the smoothing from no smoothing (i.e. identity filter for k=1, where $y^*=x^*$) to the maximum amount of smoothing (i.e. median, $k=(N+1)/2$).

The output of LUM smoother is given by

$$y^{*} = med\{x_{(k)}, x^{*}, x_{(N-k+1)}\}, \qquad (2)$$

where $x_{(k)}$ and $x_{(N-k+1)}$ are lower and upper order statistics of the ordered set.

2.2 Temporal Filters

Very important position in image processing of dynamic sequence has temporal filter. Temporal correlation of the frames can be more appropriate than the spatial correlation of pixels determined by the filter window.

In this paper, two temporal filters were used. The basic temporal structure is a set of observations consisted of three sample. The temporal median (TM3) is determined by

$$y^{\bullet} = med\{x^{\bullet}_{n-1}, x^{\bullet}_{n}, x^{\bullet}_{n+1}\}, \tag{3}$$

where n is a temporal index of frames. Thus, it is considered temporal correlation of central window pixels, i.e. previous, actual and future frames.

As generalisation of median, the weighted median filter has improved signal-detail characteristics. Then the temporal center-weighted median (TWM7), a special case of weighted median is determined by

$$y^{\bullet} = med\{x^{\bullet}_{n-2}, x^{\bullet}_{n-1}, 3\Diamond x^{\bullet}_{n}, x^{\bullet}_{n+1}, x^{\bullet}_{n+2}\}, \tag{4}$$

where $\Diamond$ is a replication operator $w\Diamond x_i = \overbrace{x_i, x_i, x_i}^{w}$. This filter is equivalent to the temporal LUM smoother for k=2 and there were used five frames of dynamic sequence.

2.3 Spatiotemporal Filters

Spatiotemporal filters are combination and logical extension of the temporal and the spatial filters. In that manner, the spatial correlation of pixels determined by the filter window of processed frame and the temporal correlation of frames are utilised, simultaneously.

The spatiotemporal median ($STM_{1,9,1}$) of 11 points is given by

$$y^{\bullet} = med\{x^{\bullet}_{n-1}, W_{n}, x^{\bullet}_{n+1}\}, \tag{5}$$

where W_n is a 3x3 window centered around the processed sample.

The spatiotemporal median ($STM_{9,9,9}$) of 27 points (i.e. a 3x3x3 cube window) is defined by

$$y^{\bullet} = med\{W_{n-1}, W_{n}, W_{n+1}\}. \tag{6}$$

The set of the observations is determined by three 3x3 windows of previous, actual and future frames.

3. Impulse Detector

In general, standard filters process every point of the image. The approaches [1,5,12,14,15] of noise filtering based on detectors use local window information and the processed pixel is filtered in the case of impulse detection, only. The parallel architecture of detector-filter system is shown on Fig.1.

The function of detector-filter structure [1,5] is defined by (7), where Val is a value of algebraic operations executed on local statistics within the detector operation window, and Tol is a control threshold.

$$\textbf{IF } Val \geq Tol \textbf{ THEN } filter \quad \textbf{ELSE } not\,filter \tag{7}$$

Thus, the central pixel is considered as noise and the filter (frequently median) determines its output value in the case of positive impulse detection, i.e. the condition for filtering is satisfied. On other hand, unchanged processed pixel is passed to the output, i.e. system works as identity filter.

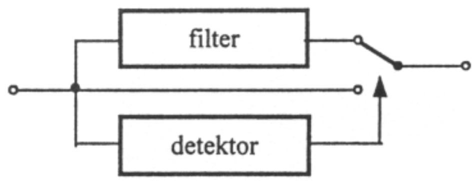

Fig.1 The detector-filter architecture

3.1 SDV Detector

Fundamentals of SDV [1] detector is based on mean and standard deviation value. The robust 3x3 SDV detector distinguishes by a simple structure and well performance of impulse detection. The rule of SDV detector is given

$$\textbf{IF } C \geq \sigma \textbf{ THEN } filter \quad \textbf{ELSE } not\,filter \tag{8}$$

where C (9a) is the absolute difference of central pixel in operation window from the mean value D, σ is the standard deviation (9b) of the pixels and N is a number of samples determined by the set of observations.

$$C = \left| x^{\bullet} - D \right| \tag{9a}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - D)^2} \tag{9b}$$

If the condition in (8) is satisfied, the central pixel is probably distorted because it is more different than the rest pixels of the operation window.

In this paper, the basic spatial structure and two spatiotemporal structures of SDV detector were used.

The spatial structure consists of nine image points determined by a 3x3 filter window of actual frame. This structure is widely used in the impulse detection of grey scale images [1] and it is most robust.

In this paper, two new spatiotemporal structures of SDV detector were introduced. These structures were designed concerning fundamentals of this detector. This approach utilises the standard deviation. Thus, it was used a 3x3x3 cube detector window. The second structure includes 15 points of three crosses (denoted ST cross) determined by processed sample of the actual, previous and future frames.

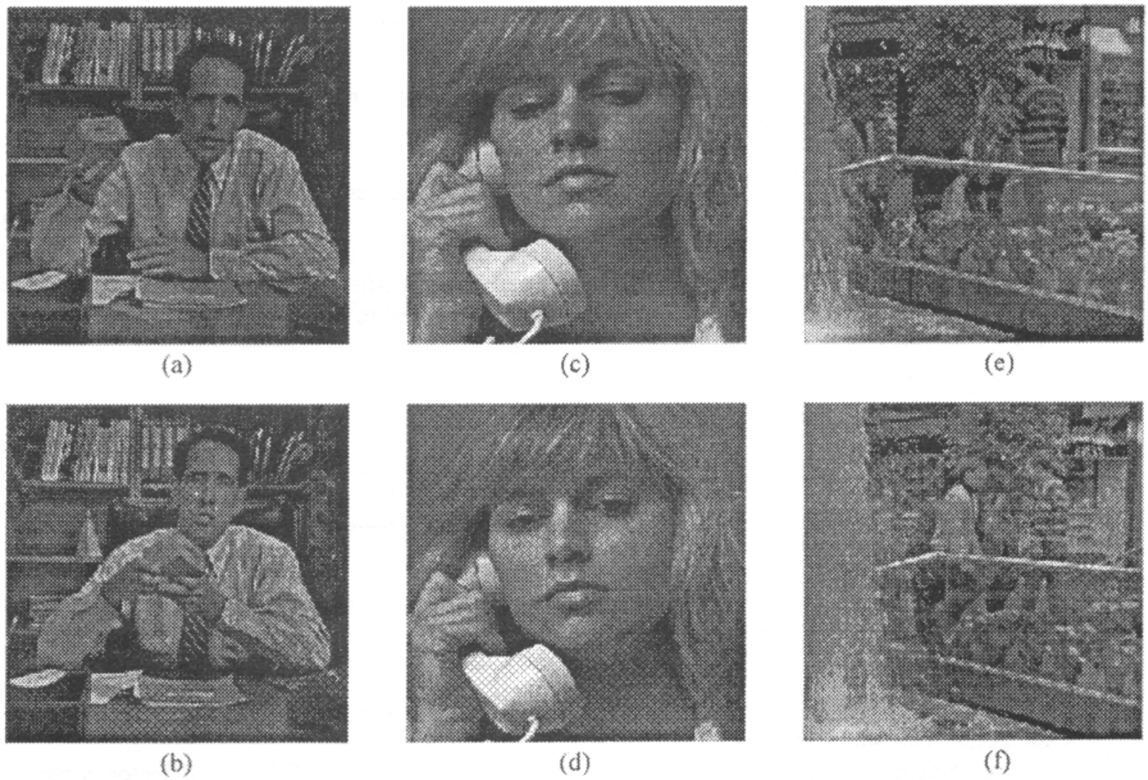

Fig.1 (a) Salesman – 5th frame (b) Salesman – 25th frame (c) Susie – 5th frame (d) Susie – 25th frame (e) People – 5th frame (f) People – 25th frame

4. Sequence description and evaluating

To illustrate the performance of the proposed method three dynamic image sequences and two types of the impulse noise were used. Every sequence consists of 30 frames. The used frames had resolution of 256x256 pixels with 8 bits/pixel gray-scale quantization.

The complexity of image sequence is evaluated according to details, edges and problem areas. In addition, the motion is considered, too.

Thus, the Salesman (Fig.1a,b) is sequence with a number of problem areas. The background consists of little monotonous fields. There are more details and edges. The considerable motion of the man in a foreground increases complexity of this sequence.

Sequence Susie (Fig.1c,d) is the most elementary, there are many monotonous fields, the problem areas are hair. Accordingly, the minimal motion is observed.

The most complexity, the large motion and a number of details are features of sequence People. Small objects such as vegetation and commodity create background. In addition, this sequence has large motion caused by combination of the motion of people and the motion of camera.

4.1 Noise models

There were used two types of impulse noise. The first one is the classical impulse noise (Fig.2b) where some of the pixels of the sequence frames were replaced by grey pixels. In case of 8 bit per pixels quantized image, the original value was replaced by random value from the interval <0,255>. The second one type of the impulse noise is the so-called salt and pepper noise (Fig.3b) where the pixels of the image were replaced by black and white pixels (by values 0 or 255). In both cases, the uniform distribution of the impulses was used.

4.2 Evaluation criteria

The most commonly used evaluation methods of filtration results are the mean absolute error (MAE) and the mean square error (MSE). The MAE (10a) evaluates the preservation of the image details and edges. If this value is high then the image is more blurred. The noise suppression is expressed by the MSE value.

The mathematical formulas of MAE and MSE are given by

$$MAE^t = \frac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} \left| o_{i,j}^t - x_{i,j}^t \right| \qquad (10a)$$

$$MSE^t = \frac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} \left(o_{i,j}^t - x_{i,j}^t \right)^2 \qquad (10b)$$

where o is the original image, x is the filtered (distorted) image, i, j are indices of image pixel position and N is the image dimension.

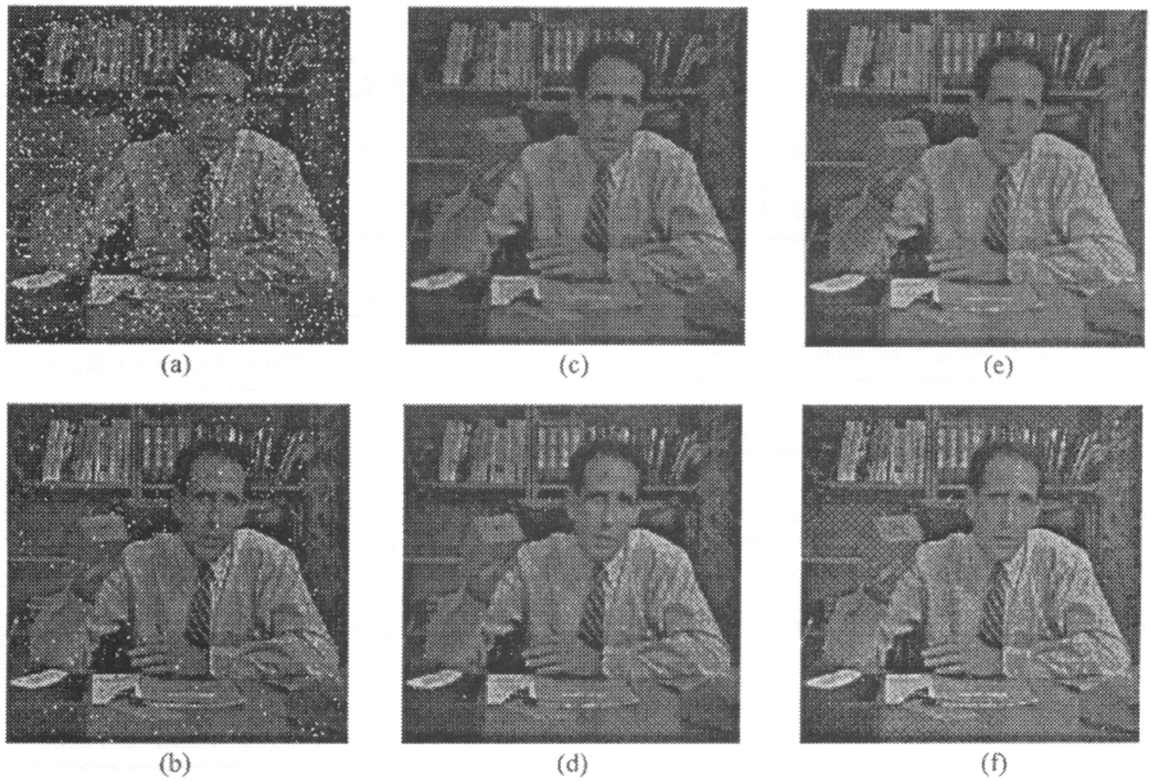

Fig.2 Salesman - 5th frame (a) Corrupted by I10 noise (b) TM3 (c) median filter (d) LUM smoother k=4 (e) $STM_{1,9,1}$ (f) Spatiotemporal cross window (STcross) of SDV detector

Indeed, the dimension of the frames used in experiments was 256x256. In the evaluation 15 pixels around the border was not used, therefore the N=226. The pixels bypass around the border was on the ground of border effect [7]. The MAE and MSE on the whole sequence [3] are defined as follows

$$MAE = \frac{1}{M}\sum_{t=1}^{M} MAE^t \qquad (11a)$$

$$MSE = \frac{1}{M}\sum_{t=1}^{M} MSE^t \qquad (11b)$$

where M is the number of frames in sequence and t is the frame number.

The main drawback of the above two evaluation criteria that they do not express the depreciation of the motion in sequence. They evaluate only the individual sequence frames. On that account, it would be good to define another criteria that would express the motion conservation of the sequence. This paper introduces a new method of evaluation of this subject. This criterion based on statistical cross correlation is defined:

$$E^t = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{i,j}^t \qquad (12a)$$

$$\sigma^t = \sqrt{\frac{1}{N^2}\sum_{i-1}^{N}\sum_{j-1}^{N}\left(x_{i,j}^t - E^t\right)^2} \qquad (12b)$$

$$R^t = \left| \frac{\frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{i,j}^t\, x_{i,j}^{t+1} - E^t\, E^{t+1}}{\sigma^t\, \sigma^{t+1}} \right| \qquad (12c)$$

where E^t is the mean value of the t^{th} frame of the sequence, σ^t is the standard deviation of the t^{th} frame and R^t is the statistical cross correlation between the t^{th} frame and the $(t+1)^{th}$ frame. In like manner as above, the whole cross correlation is defined as follows:

$$R = \frac{1}{M}\sum_{t=1}^{M} R^t \qquad (13)$$

The closer is the cross correlation coefficient to one the more static is the sequence. It means that particular frames more resembles themselves, therefore the sequence contains less motion. The purpose of the filtration is to achieve the smallest difference of cross correlation coefficients between the original noise-free sequence and the filtered sequence, as follows:

$$\Delta R = \left| R^o - R^f \right| \qquad (14)$$

where R^o and R^f are the statistical cross-correlations of the original and filtered sequence, respectively.

Table 1 shows that sequence People is characterised by the largest motion. Thus, the value of correlation R is markedly less than the value of correlation of sequences Salesman and Suzy.

In Table 2 are expressed deviations between original and noised sequences. These deviations are considered in three-dimensional (3D) measure. They were evaluated by MAE and MSE criteria (11). The 10% impulsive noise with variable random value is denoted by I10 mark and 20% salt and pepper noise is denoted as BW20 (black and white). Thus, the percent expression is equivalent to a number of corrupted points of every frame.

Table 1 Motion evaluating of original sequences

Sequence	Salesman	Susie	People
R	0.979	0.983	0.878

Table 2 Conventional evaluating of noised sequences

Noise	I10		BW20	
Sequence	*MAE*	*MSE*	*MAE*	*MSE*
Salesman	7.287	825.1	23.101	3539.3
Susie	6.738	688.4	23.021	3270.8
People	7.069	772.8	22.473	3351.7

Table 3 Correlation evaluating of noised sequences

Noise	I10		BW20	
Sequence	*R*	*ΔR*	*R*	*ΔR*
Salesman	0.583	0.396	0.215	0.764
Susie	0.646	0.337	0.242	0.741
People	0.526	0.352	0.198	0.680

The motion details are shown in Table 3. The cross correlation coefficient ΔR was used. In next section, the evaluation of variance between filtered sequences and desired estimates is evaluated by above-mentioned criteria.

5. Experimental Results

Several experiments were performed using the proposed methods. Results of these experiments show that best performance of noise removing in environments corrupted by I10 impulsive noise was achieved by spatial structures of LUM smoothing filter. These results approved assumption following from excellent smoothing characteristics of LUM smoothers [2]. By temporal filters well MAE values were obtained. Thus, signal details are preserved, but it is possible to observe some impulses. However, these filters have well detail preservation in sequences with the small motion, where a little blurring is introduced, only. The spatiotemporal filters, the combination of spatial filters and temporal filters achieve comparable results with spatial median. The $STM_{1,9,1}$ has better properties than a median of cube window, because processed pixel is replaced by the median of a smaller set. Thus, blurring is reduced. In addition, $STM_{1,9,1}$ better utilises temporal context of the set of observation.

Table 4 Evaluating of filtered sequences Salesman

Noise	I10			BW20		
Filter	*MAE*	*MSE*	*ΔR*	*MAE*	*MSE*	*ΔR*
TM3	3.086	109.1	0.029	9.338	1121.4	0.254
TWM7	**2.029**	129.0	0.054	9.619	1351.5	0.378
Median	4.097	64.3	**0.003**	4.766	106.7	0.032
LUM k=3	**2.029**	61.3	0.033	5.959	625.5	0.312
LUM k=4	2.648	46.1	0.009	3.795	168.1	0.089
$STM_{1,9,1}$	3.303	**38.6**	0.004	**3.657**	**56.4**	**0.008**
$STM_{9,9,9}$	4.237	59.6	0.011	4.400	64.7	0.010

Table 5 Evaluating of filtered sequences Susie

Noise	I10			BW20		
Filter	*MAE*	*MSE*	*ΔR*	*MAE*	*MSE*	*ΔR*
TM3	2.457	89.2	0.022	7.671	853.6	0.203
TWM7	2.198	109.8	0.041	8.530	1054.6	0.300
Median	3.097	30.9	0.006	3.541	58.7	0.012
LUM k=3	**1.521**	34.0	0.013	5.229	537.5	0.260
LUM k=4	1.956	**21.2**	**0.003**	**2.921**	122.7	0.059
$STM_{1,9,1}$	2.831	24.2	0.008	3.098	35.4	**0.003**
$STM_{9,9,9}$	3.265	29.2	0.011	3.353	**31.1**	0.010

Table 6 Evaluating of filtered sequences People

Noise	I10			BW20		
Filter	*MAE*	*MSE*	*ΔR*	*MAE*	*MSE*	*ΔR*
TM3	5.882	194.4	0.035	11.535	1049.4	0.146
TWM7	4.231	181.8	0.014	10.944	1221.2	0.267
Median	5.161	76.7	0.038	5.729	113.8	**0.014**
LUM k=3	**2.371**	61.2	**0.009**	6.138	582.4	0.257
LUM k=4	3.258	**50.7**	0.022	**4.370**	165.2	0.049
$STM_{1,9,1}$	5.292	75.6	0.054	5.673	**94.4**	0.043
$STM_{9,9,9}$	6.982	120.8	0.088	7.104	126.8	0.086

The best results in the environments corrupted by salt and pepper noise (BW20) were achieved by filters with marked smoothing characteristics. So, the spatial median filter and spatiotemporal structures have better versatility than others methods. However, spatiotemporal filters achieve well performance of signal preservation in the sequences with the smaller motion. Actually, by the cube 3x3x3 median was obtained the best MSE value for sequence Susie.

Noise removing of temporal filters is inefficient. It is a consequence of the set of observation. Three, respectively five image points within the filter window are insufficient. In addition, the set consists of outliers determined by the motion, too.

Excellent smoothing and detail preserving properties of LUM smoother excel in environments with impulse noise with variable values. In the environments distorted by 20% salt and pepper noise, these excellent features are rejected. Even thought, the best MAE value of sequence Susie was obtained by LUM smoother with tuning parameter k=4. This result was obtained due to monotone fields and the low motion, too.

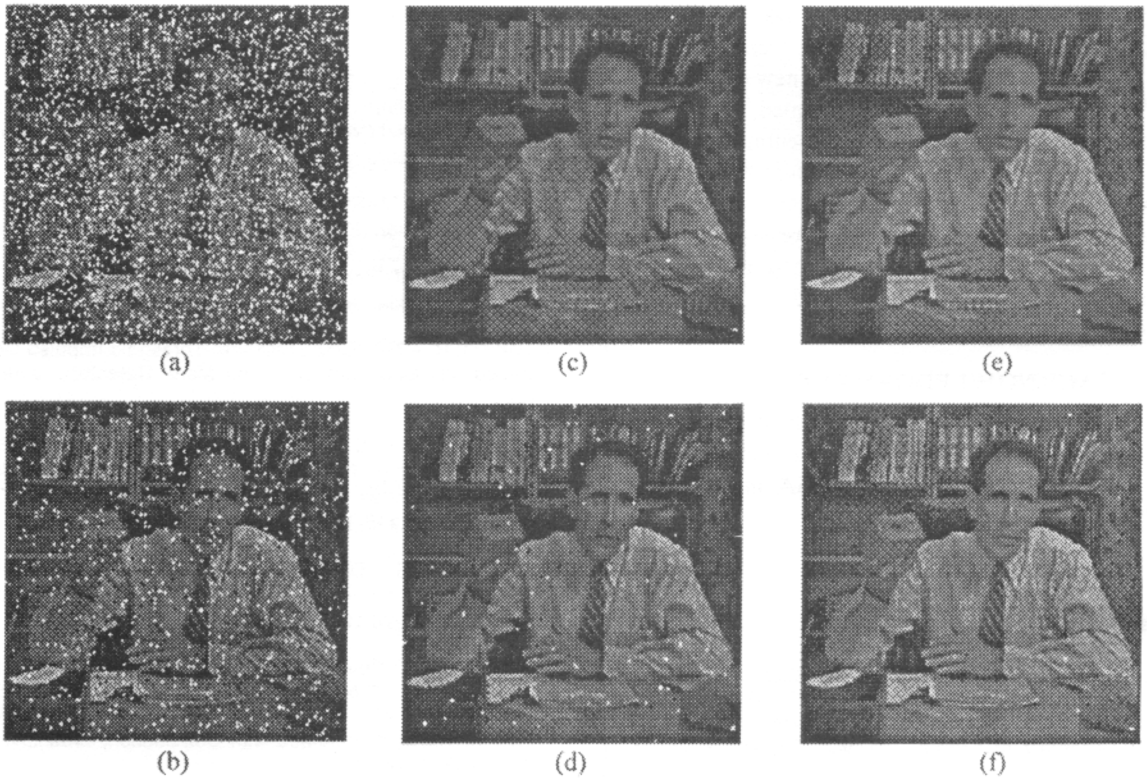

Fig.3 Salesman - 5th frame (a) Corrupted by BW20 noise (b) TM3 (c) median filter (d) LUM smoother k=4 (e) $STM_{1,9,1}$ (f) Spatiotemporal 3x3x3 cube window of SDV detector

Table 7 Sequence Salesman processed by SDV detector

Noise	I10			BW20		
Window	*MAE*	*MSE*	*ΔR*	*MAE*	*MSE*	*ΔR*
3x3	2.027	56.2	0.020	2.461	99.1	0.053
ST cross	**1.162**	**28.9**	**0.013**	2.007	72.9	0.039
3x3x3	1.398	38.6	**0.013**	**1.960**	**69.1**	**0.037**

Table 8 Sequences Susie processed by SDV detector

Noise	I10			BW20		
Window	*MAE*	*MSE*	*ΔR*	*MAE*	*MSE*	*ΔR*
3x3	1.458	29.7	0.008	1.554	56.4	0.027
ST cross	1.053	20.4	0.006	1.185	34.5	0.015
3x3x3	**0.927**	**18.4**	**0.005**	**1.091**	**30.0**	**0.013**

Table 9 Sequences People processed by SDV detector

Noise	I10			BW20		
Window	*MAE*	*MSE*	*ΔR*	*MAE*	*MSE*	*ΔR*
3x3	2.397	59.0	0.004	2.561	92.9	0.025
ST cross	1.800	**42.9**	0.013	2.000	65.3	0.011
3x3x3	**1.724**	43.0	**0.011**	**1.777**	**54.8**	**0.010**

Mentioned results from Table 4-6 can be improved by use of impulse detector. In this paper, the 3x3 spatial structure and two spatiotemporal filter window (3x3x3 window and window consisting of three five points crosses – ST cross) were used. In case of impulse detection, the 3x3 spatial median filter was used.

From results from Table 7-9 was confirmed that spatiotemporal structures of SDV detector have excellent performance of impulse detection. Thus, the best results were obtained. Excellent properties of spatiotemporal structures of SDV detector are resulting from principle of SDV detector. The standard deviation is used and there is needed a set of more elements (27 elements of 3x3x3 cube window and 15 elements of spatiotemporal cross-window). In addition, the motion is considered by spatiotemporal window.

6. Conclusion

In this paper, the spatial, temporal and spatiotemporal rank-order-based filters for use in environments corrupted by impulse noise were presented. Image sequences can be considered as spatiotemporal data.

Thus, in depend on amount of the motion it is possible to use appropriate filter. In sequences with a little motion temporal filters achieved well performance. However, in applications of highly corrupted sequences (BW20 noise) performance of temporal filters was insufficient. In sequences of highly noise and considerable motion spatial and spatiotemporal filters acquired best results.

Obtained results were improved by using of impulse detectors. In this paper were introduced and presented two new spatiotemporal structures of the robust SDV detector. By this way were obtained excellent results.

Performance of various methods was evaluated through objectionable criteria. In this paper were used 3-D extension of MAE and MSE. In addition, a new criterion of motion evaluating was developed and presented.

Furthermore, the introducing of neural networks [8-10,14,16] will be considered in near future. The neural networks was used in a number of application such as acoustic signal recognition [8], data compression [9], and others... Thus, the neural networks based on optimal training set [10,16] would be introduced to the image processing of noisy dynamic sequences.

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