Video Denoising by Fuzzy Directional Filter Using the DSP EVM DM642

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Abstract. We present a new 3D Fuzzy Directional (3D-FD) algorithm for the denoising of video colour sequences corrupted by impulsive noise. The proposed approach consists of the estimations of movement levels, noise in the neighborhood video frames, permitting to preserve the edges, fine details and chromaticity characteristics in video sequences. Experimental results show that the noise in these sequences can be efficiently removed by the proposed 3D-FD filter, and that the method outperforms other state of the art filters of comparable complexity on video sequences. Finally, hardware requirements are evaluated permitting real time implementation on DSP EVM DM642.

Keywords: Fuzzy logic, Directional Processing, Impulsive Noise.

1 Introduction

Video signals are corrupted by noise from the capturing devices or during transmission due to random thermal or other electronic noises. Noise reduction can considerably improve visual quality and facilitate the subsequent processing tasks, such as video compression. There are many existing video denoising approaches employed for impulsive noise suppression in images and video sequences [1-11]. Another problem, which is exist here, is possible camera moving or occlusion that produce the temporal changes, which together spatial fine details and edges, and texture hinder traditional technique and demand to introduce novel adaptive frameworks.

The proposed 3D-FD filter is based on fuzzy set theory and order vector statistic technique in processing of RGB colour video sequences, detecting the noise and movement levels, and permitting to suppress impulsive noise. The 3D-FD algorithm consists of use of novel 2D-FD filter as a first (spatial) stage applied to $t-1$ frame. At the second (temporal) stage of algorithm, the filtering result of first stage should be employed in filtering of next t frame of the video sequence. As a final stage, the present frame is filtered applying again the 2D-FD filter, which permits noise suppression in a current frame. Numerical simulations demonstrate that new 3D-FD filter can outperform several filtering approaches in processing the video colour sequences in terms of noise suppression, edge and fine detail preservation, and colour retention.

Finally, the Real-Time evaluation was realized using Texas Instruments EVM DM642 presenting good capabilities in the real-time environment.

2 Proposed 3D Fuzzy Directional (3D-FD) Filter

The 3D Fuzzy Directional (3D-FD) procedure employs a 2D-FD filter as a first (spatial) stage in the initial frame of video sequence. After, the temporal stage of the algorithm, proposed 2D-FD algorithm should be used again to suppress the non-stationary noise left during the temporal stage of the procedure.

Let introduce *gradients* and *angle variance* as absolute differences to represent the level of similarity among different pixels. Next, we calculate the gradient for each direction $\gamma = \{N, E, S, W, NW, NE, SE, SW\}$ according to Figure 1a. We employ not only one *basic gradient* for any direction, but also four *related gradient*, with (k, l) values $\{-2, -1, 0, 1, 2\}$ [12,13]. The *angle variance* is computed for each a channel in such a way where we omit two of the three channels in the case of each a RGB colour frame. We use two neighbor frames of a video sequence to calculate the movement and noise fuzzy levels of a central pixel. A 5x5x2 sliding window is formed by *past* and *present* frames (see Figure 1b),

The *gradient* can be computed as,

$$G_{(k,l)}^\beta = \left| A_{(i+k,j+l)}^\beta - B_{(i+k,j+l)}^\beta \right|, \quad (1)$$

where $G_{(k,l)}^\beta$ can be a gradient ∇_γ^β or a *gradient difference value* $\lambda_{(k,l)}^\beta$ (in the case of 3D), $A_{(i+k,j+l)}^\beta$ and $B_{(i+k,j+l)}^\beta$ are the pixels in 2D window processing (see Figure 1a) or the pixels in $t-1$ and t frames of sequence (see Figure 1b), β is the RGB colour space, and γ marks any chosen direction according to indexes $(k, l) \in \{-2, -1, 0, 1, 2\}$.

The *angle variance* is calculated as follows:

$$\phi_{(k,l)}^\beta = \arccos \left[\frac{2(255)^2 + A_{(i+k,j+l)}^\beta \cdot B_{(i+k,j+l)}^\beta}{\left(2(255^2) + (A_{(i+k,j+l)}^\beta)^2\right)^{1/2} \cdot \left(2(255^2) + (B_{(i+k,j+l)}^\beta)^2\right)^{1/2}} \right]. \quad (2)$$

where $\phi_{(k,l)}^\beta$ can be an angle variance $\theta_{(k,l)}^\beta$ or an absolute difference vectorial (angle variance in the case of 3D) value $\phi_{(k,l)}^\beta$.

Figure 1a exposes the employed pixels in 2D processing procedure in the case of *SE* direction for the *basic* and *related* components. The basic gradient value for *SE* direction is $\nabla_{(1,1)}^\beta x(i, j) = \nabla_{SE(b)}^\beta$ and the related gradients and angle variance values are given by $F_{(0,2)}^\beta x(i-1, j+1) = \nabla_{SE(r_1)}^\beta = \theta_{SE(r_1)}^\beta$, $F_{(2,0)}^\beta x(i+1, j-1) = \nabla_{SE(r_2)}^\beta = \theta_{SE(r_2)}^\beta$, $F_{(0,0)}^\beta x(i-1, j+1) = \nabla_{SE(r_3)}^\beta = \theta_{SE(r_3)}^\beta$, and $F_{(0,0)}^\beta x(i+1, j-1) = \nabla_{SE(r_4)}^\beta = \theta_{SE(r_4)}^\beta$.

In the case of 3D procedure, we calculate the *absolute difference gradient values* $\nabla_\gamma^{\beta'}$ of a central pixel with respect to its neighbours for a 5x5x1 window processing.

Fig. 1. Windows processing, a) Neighbourhood pixels, *basic* (b) and *related* (r_1, r_2, r_3, r_4) directions for *gradient* and *angle* variance values, and b) Processing frames in the proposed 3D-FD filter

Using *angle* variance value $\phi_{(k,l)}^\beta$, we can characterize the *absolute vectorial variance* $\nabla_\gamma^{u\beta}$. The *absolute difference gradient* value and *absolute vectorial variance* for the *SE* (*basic*) direction are given by values $\nabla_{SE(basic)}^{t\beta} = \nabla_{(1,1)}^{t\beta} \lambda_{(0,0)}^\beta = |\lambda_{(0,0)}^\beta - \lambda_{(1,1)}^\beta|$ and $\nabla_{SE(basic)}^{u\beta} = \nabla_{(1,1)}^{u\beta} \phi_{(0,0)}^\beta = |\phi_{(0,0)}^\beta - \phi_{(1,1)}^\beta|$, respectively. The same reasoning done by $\nabla_{SE(basic)}^{r\beta}$ with respect to $\nabla_{SE(basic)}^\beta$ is realized also by value $\nabla_{SE(basic)}^{r'\beta}$.

We introduce BIG (B) and SMALL (S) fuzzy sets to estimate the noise presence in a central pixel for each a sliding window. A big membership degree (≈ 1) in the SMALL set shows that the central pixel is free of noise, and a large membership degree in the BIG set shows that the central pixel is noisy one with large probability. To calculate membership degrees for fuzzy gradient and fuzzy vectorial values, we use the following Gaussian membership functions:

$$\mu(F_\gamma^\beta \text{SMALL}) = \begin{cases} 1, & F_\gamma^\beta < med_F \\ \exp\left[-\left[(F_\gamma^\beta - med_F)^2 / 2\sigma_F^2\right]\right], & \text{otherwise} \end{cases}, \quad (3)$$

$$\mu(F_\gamma^\beta \text{BIG}) = \begin{cases} 1, & F_\gamma^\beta > med_F \\ \exp\left[-\left[(F_\gamma^\beta - med_F)^2 / 2\sigma_F^2\right]\right], & \text{otherwise} \end{cases}, \quad (4)$$

where $\sigma_1^2=1000$, $med_1=60$ and $med_2=10$ for fuzzy gradient sets BIG and SMALL, respectively, $\sigma_2^2=0.8$, $med_3=0.1$ and $med_4=0.615$ for fuzzy angular deviation sets BIG and SMALL, respectively. The values $med_3=0.01$ and $med_4=0.1$ are changed in the case of use of 3D-FD filter. These values were found according to optimal PSNR and MAE values.

Table 1 presents the novel fuzzy rules that are based on gradient and angle variance values to determine if the central component is noisy or present local movement [3].

Table 1. Fuzzy rules used in the proposed 2D-FD and 3D-FD filters

<p>Fuzzy Rule 1 introduces the membership level of $x_{(i,j)}^\beta$ in the set BIG for any γ direction: IF $(\nabla_\gamma^\beta B \otimes \nabla_{\gamma(r_1)}^\beta S \otimes \dots \otimes \nabla_{\gamma(r_4)}^\beta B) \otimes_1 (\theta_\gamma^\beta B \otimes \theta_{\gamma(r_1)}^\beta S \otimes \dots \otimes \theta_{\gamma(r_4)}^\beta B)$, THEN the fuzzy gradient-vectorial value $\nabla_\gamma^{\beta F} \theta_\gamma^{\beta F} B$.</p>
<p>Fuzzy Rule 2 presents the <i>noisy factor</i> gathering eight fuzzy gradient-directional values calculated for each a direction: IF $\nabla_N^{\beta F} \theta_N^{\beta F} B \oplus \nabla_S^{\beta F} \theta_S^{\beta F} B \oplus \dots \oplus \nabla_{SE}^{\beta F} \theta_{SE}^{\beta F} B \oplus \nabla_{SW}^{\beta F} \theta_{SW}^{\beta F} B$ THEN the noisy factor $r^\beta B$.</p>
<p>Fuzzy Rule 3 characterizes the <i>movement and noise confidence</i> in a central pixel by neighbour fuzzy values in any γ by use the <i>FIRST fuzzy gradient-vectorial difference value</i> $(\nabla_\gamma^{\beta F} \nabla_\gamma^{\alpha F})_{FIR}$: IF $(\nabla_\gamma^{\beta F} B \otimes \nabla_{\gamma(r_1)}^{\beta F} S \otimes \nabla_{\gamma(r_2)}^{\beta F} S \otimes \nabla_{\gamma(r_3)}^{\beta F} B \otimes \nabla_{\gamma(r_4)}^{\beta F} B) \otimes_1 (\nabla_\gamma^{\alpha F} B \otimes \nabla_{\gamma(r_1)}^{\alpha F} S \otimes \nabla_{\gamma(r_2)}^{\alpha F} S \otimes \nabla_{\gamma(r_3)}^{\alpha F} B \otimes \nabla_{\gamma(r_4)}^{\alpha F} B)$, THEN $(\nabla_\gamma^{\beta F} \nabla_\gamma^{\alpha F})_{FIR} B$.</p>
<p>Fuzzy Rule 4 characterizes the <i>no movement confidence</i> in a central pixel in any γ direction, distinguishing different areas, such as, uniform region, edge or fine detail by use the <i>SECOND fuzzy gradient-vectorial difference value</i> $(\nabla_\gamma^{\beta F} \nabla_\gamma^{\alpha F})_{SEC}$: IF $(\nabla_\gamma^{\beta F} S \otimes \nabla_{\gamma(r_1)}^{\beta F} S \otimes \nabla_{\gamma(r_2)}^{\beta F} S) \oplus (\nabla_\gamma^{\alpha F} S \otimes \nabla_{\gamma(r_1)}^{\alpha F} S \otimes \nabla_{\gamma(r_2)}^{\alpha F} S)$, THEN $(\nabla_\gamma^{\beta F} \nabla_\gamma^{\alpha F})_{SEC} S$.</p>
<p>Fuzzy Rule 5 estimate the movement and noise level in a central component using the fuzzy values determined for all directions by use the <i>fuzzy noisy factor</i> r^β: IF $(\nabla_{SE}^{\beta F} \nabla_{SE}^{\alpha F})_{FIR} B \oplus (\nabla_S^{\beta F} \nabla_S^{\alpha F})_{FIR} B \oplus \dots \oplus (\nabla_N^{\beta F} \nabla_N^{\alpha F})_{FIR} B$, THEN $r^\beta B$.</p>
<p>Fuzzy Rule 6 defines the <i>no movement confidence factor</i> η^β: IF $(\nabla_{SE}^{\beta F} \nabla_{SE}^{\alpha F})_{SEC} S \oplus (\nabla_S^{\beta F} \nabla_S^{\alpha F})_{SEC} S \oplus \dots \oplus (\nabla_N^{\beta F} \nabla_N^{\alpha F})_{SEC} S$, THEN $\eta^\beta S$.</p>
<p>where $A \otimes B = A \text{ AND } B$, $A \otimes_1 B = \min(A, B)$, $A \oplus B = \max(A, B)$, and PB and QS denote that value P is BIG and value Q is SMALL, respectively.</p>

The parameters r^β and η^β can be effectively applied in the decision: if a central pixel component is noisy, or is in movement, or is a free one. Fuzzy Rules 1 and 2, and from 3 to 6 determine the 2D-FD and 3D-FD algorithm based on fuzzy parameters, respectively.

The noisy factor is used as a threshold to distinguish among a noisy pixel and a free noise one. If $r^\beta \geq 0.3$, the filtering procedure is applied employing the fuzzy gradient-vectorial values as weights. The fuzzy weights are used in the standard negator function $\varsigma(x) = 1 - x$, $x \in [0, 1]$ defined as $\rho(\nabla_\gamma^{\beta F} \theta_\gamma^{\beta F}) = 1 - \nabla_\gamma^{\beta F} \theta_\gamma^{\beta F}$, this value origins a fuzzy membership value in a new fuzzy set defined as FREE (free noise). The fuzzy weight for central pixel in FREE fuzzy set is $\rho(\nabla_{(0,0)}^{\beta F} \theta_{(0,0)}^{\beta F}) = 3 \cdot \sqrt{1 - r^\beta}$. In opposite case, the output is presented as unchanged central pixel $y_{output}^\beta = x_{\gamma}^{\beta(j)}$.

To enhance the noise suppression capabilities of the proposed 3D filter, we use at the final stage the 2D-FD filter that permits to decrease the influence of the non-stationary noise left by temporal filter. Table 2 shows some modifications of the

Table 2. Parameters of 2D-FD Filter

2D-FD Filter	
Initial stage	Final stage
$r^\beta \geq 0.3$	$r^\beta \geq 0.5$
$\rho(\nabla^\beta \theta^\beta) = \left(\sum_{\gamma} \rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F}) + 3 \cdot \sqrt{1-r^\beta} \right) / 2$	$\rho(\nabla^\beta \theta^\beta) = \left(\sum_{\gamma} \rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F}) + 5 \cdot \sqrt{1-r^\beta} \right) / 2$
$\rho(\nabla_{(0,0)}^{\beta F} \theta_{(0,0)}^{\beta F}) = 3 \cdot \sqrt{1-r^\beta}$	$\rho(\nabla_{(0,0)}^{\beta F} \theta_{(0,0)}^{\beta F}) = 5 \cdot \sqrt{1-r^\beta}$
If condition $sum^\beta \geq \rho(\nabla^\beta \theta^\beta)$ until $\rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F})^{(2)}$ is not satisfied, <i>total weight</i> is updated according to $\rho(\nabla^\beta \theta^\beta) = \left(\rho(\nabla^\beta \theta^\beta) - \rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F})^{(1)} \right) / 2$.	

2D-FD applied after the 3D-FD that should be realized because of the non-stationary nature of noise according the best PSNR and MAE criteria results.

The output of 2D-FD filter is formed by selection of one of the neighbour pixels or central component. The condition $j \leq 2$ avoids the selection of the farther pixels, otherwise, the total weight is upgraded. Finally, the algorithm of 2D-FD filter is realized as follows:

- 1) Let calculate the fuzzy weights by use an ordering procedure: $x_{\gamma}^{\beta} = \{x_{SW}^{\beta}, \dots, x_{(i,j)}^{\beta}, \dots, x_{NE}^{\beta}\}$ and $x_{\gamma}^{\beta(1)} \leq x_{\gamma}^{\beta(2)} \leq \dots \leq x_{\gamma}^{\beta(9)}$ implies that the fuzzy weights are given by $\rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F})^{(1)} \leq \rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F})^{(2)} \leq \dots \leq \rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F})^{(9)}$, where $\gamma = \{N, E, S, W, (i, j), NW, NE, SE, SW\}$, permitting to remove the values more outlying from the central pixel (i, j) .
- 2) We define $sum^{\beta} + = \rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F})^{(9)}$ with $j=9$, decreasing j from 9 to 1 that is valid until the condition $sum^{\beta} \geq \rho(\nabla^\beta \theta^\beta)$ can be satisfied (where $\rho(\nabla^\beta \theta^\beta) = \left(\sum_{\gamma} \rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F}) + 3 \cdot \sqrt{1-r^\beta} \right) / 2$). When j satisfies this condition, the j th ordered value $x_{\gamma}^{\beta(j)} = y_{output}^{\beta}$ is selected as the output filtered value. If $j \leq 2$, the next step of algorithm is realized.
- 3) If $j \leq 2$, it should be computed the weights $\rho_{j \leq 2}(\nabla^\beta \theta^\beta) = \left(\rho(\nabla^\beta \theta^\beta) - \rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F})^{(1)} - \rho(\nabla_{\gamma}^{\beta F} \theta_{\gamma}^{\beta F})^{(2)} \right) / 2$, defining $sum^{\beta} + = \rho(\nabla_{\gamma}^{\beta(j)} \theta_{\gamma}^{\beta(j)})$, and restore $j=9$, decreasing j from 9 to 1 that is valid until the condition $sum^{\beta} \geq \rho(\nabla^\beta \theta^\beta)$. When j satisfies this condition, the j th ordered value $x_{\gamma}^{\beta(j)} = y_{output}^{\beta}$ is selected as the output filtered value.

Figure 2 exposes the block diagram of the proposed 3D-FD filter, where the j -th component pixel should be chosen, if it satisfies the proposed conditions, guaranteeing edges and fine detail preservation according to ordering criterion in the selection of the nearest pixels to the central one in $t-1$ and t frames.

3 Experimental Results

The described 3D-FD filter has been evaluated, and its performance has been compared with different filters proposed in literature [1-6, 10-13].

Fig. 2. Block diagram of proposed 3D Fuzzy Directional (3D-FD) algorithm

The performance criteria used to compare the restoration performance of various filters were the *peak signal-to-noise ratio* (PSNR) for evaluation of noise suppression, the *mean absolute error* (MAE) for quantification of edges and detail preservation, the *mean chromaticity error* (MCRE) for evaluation of chromaticity retention, and the *normalized color difference* (NCD) for quantification of color perceptual error [1-6].

The 176x144 QCIF video colour sequence “Miss America” was contaminated artificially by 5 and 15% of impulsive noise in independent way for each a channel.

Table 3 shows the performance results in the case of averaging of 100 frames of video sequence “Miss America”. In the case of 5% of degradation, the proposed 3D-FD filter provides the best restoration performance, and for 15% of impulsive noise, one can see that the best PSNR performance is given by 3D-AVDATM filter but the best detail preservation and chromaticity properties criteria are realized by proposed 3D-FD filter. Figure 3 depicts the zoomed filtered frames of video sequence “Miss America” in the case of 15% of impulsive noise, where the proposed 3D-FD filter preserves better preservations of edges and fine details, and chromaticity properties against other filters.

To provide better evaluation capabilities, we have implemented some promising algorithms on DSP to a Real-Time evaluation with real video sequences. So, this can provide reliability of the proposed filter against some better algorithms found in scientific literature. Table 4 presents the processing time values in filtering of 20 video frames for several filters using the Texas Instruments EVM DM642. From these results, we observe that the proposed 3D-FD filter presents good capabilities in the real time environment.

Table 3. Performance results in the video sequence “Miss America” using different filters

Filters	5% of impulsive noise				15% of impulsive noise			
	PSNR	MAE	NCD	MCRE	PSNR	MAE	NCD	MCRE
3D-FD	39.59	0.372	0.002	0.003	34.33	1.180	0.005	0.008
3D-MF	35.12	2.514	0.009	0.013	34.36	2.701	0.010	0.014
3D-VMF	34.86	2.544	0.009	0.013	34.18	2.708	0.010	0.014
3D-VDKNNVM[10]	33.48	3.106	0.011	0.015	32.37	3.428	0.012	0.016
3D-GVDF [2]	33.76	2.905	0.011	0.014	33.70	2.847	0.010	0.014
3D-AVDATM [11]	36.97	1.112	0.004	0.006	35.38	1.714	0.006	0.009
3D-ATM [12,13]	35.22	2.569	0.009	0.013	34.42	2.767	0.010	0.013
3D-KNNF [12,13]	37.21	1.909	0.007	0.010	30.09	3.838	0.014	0.020

Fig. 3. Subjective visual qualities of restored 10th frame of “Miss America” video sequence, a) Zoomed image region contaminated by **impulsive noise of 15% intensity**, b) Designed 3D-FD, c) 3D-VMF, d) 3D-GVDF, e) 3D-AVDATM, f) 3D-ATM**Table 4.** Time values needed for processing 20 frames of video sequence “Miss America”

Filters	Processing time in seconds		
	Maximum	Average	Total
3D-FD	7.533	7.440	148.806
3D-MF	0.0065	0.0057	0.114
3D-VMF	0.075	0.075	1.496
3D-GVDF [2]	28.52	25.6	512.02
3D-ATM	0.1347	0.134	2.681
3D-AVDATM	25.551	24.867	497.356
3D-KNNF [12,13]	0.103	0.102	2.04

4 Conclusions

The proposed 3D-FD filter uses fuzzy set theory and order vector statistic technique to provide better performance in noise suppression, edge and fine detail preservation, and chromaticity characteristics for video colour sequence denoising in comparison with existed filtering approaches in terms of objective criteria, as well subjective perception by human viewer. Finally, the Real-Time evaluation was realized using EVM DM642 presenting good capabilities in the real-time environment.

Acknowledgments. This work is supported by National Polytechnic Institute of Mexico and CONACyT (project 81599).

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