AN ADAPTIVE METHOD FOR VIDEO DENOISING BASED ON THE ICI RULE

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Abstract: *This paper presents an adaptive video denoising technique based on the intersection of confidence intervals (ICI) rule used for adaptive filter support size calculation. The method is applied to three real-life video signals and its denoising performance is compared to a fixed size filter support based method resulting in a significant estimation error reduction in terms of the average frame peak signal-to-noise ratio (PSNR) improvement. The average frame PSNR obtained by using the here presented ICI based video denoising method is increased by up to 14.64 dB and by up to 23.74 dB when compared to the fixed size filter support based method. Furthermore, unlike the fixed size filter support based method, the adaptive ICI based method is shown to be efficient in a moving object edge preserving, while avoiding its blurring. The method performs well for both video signals obtained by recording stationary scenes, and video signals of moving objects, which are far more often encountered in practical applications, whereas the fixed size filter support based method is limited only to video signals of stationary scenes.*

Keywords:
– intersection of confidence intervals (ICI) rule
– image denoising
– video denoising
– adaptive filtering
– temporal filtering
– edge preserving

1. INTRODUCTION

Image and video denoising, although one of the oldest fields of interest in image (video) processing, still remains a key challenge in spite of numerous recently proposed methods (a review of which can be found in [1]). Images taken in poor conditions often get corrupted by noise. Image noise can also be caused by electronic hardware (shot noise) and the channels during the transmission (thermal noise) [2]. The goal of any denoising technique is to provide a noise-free image or its best possible estimate.

The here presented video denoising approach is based on the intersection of confidence intervals (ICI) rule used for adaptive filter support size calculation [3, 4, 5]. It considers a video frame pixel over time and calculates the filter support size using the ICI rule for each pixel in each frame independently, followed by 1D filtering.

According to the ICI rule, average change in the considered pixel value over time is considered to be caused by the change in the recorded scene containing important video information. On the other hand, a small change in the considered pixel value is considered to be caused by noise. The ICI based method is an automatic adaptive tool for selecting appropriate adaptive filter support size for each pixel in each frame in order to reduce video estimation error.

The paper is organized as follows: Section 2 presents the ICI rule; In Section 3 the proposed video denoising algorithm is described; Section 4 gives the experimental results for three test videos and also analyzes the performance of the denoising method. The conclusion is given in Section 5.

2. THE ICI RULE

Let us consider a video pixel $x(i, j, k)$, where i and j stand for the pixel indices, and k for the video frame index, respectively. The adaptive filter support size for each video pixel and each frame is calculated using the ICI rule which introduces a sequence of confidence intervals, independently to its left-hand and right-hand side for the considered frame pixel. The confidence intervals limits (lower and upper, respectively) are calculated as [4]:

$$L_n(i,j,k) = \overline{X}_n(i,j,k) - z_c \frac{\sigma}{\sqrt{n}} \tag{1}$$

$$U_n(i,j,k) = \overline{X}_n(i,j,k) + z_c \frac{\sigma}{\sqrt{n}} \tag{2}$$

The parameter z_c defines the confidence interval length, while the parameter σ is the standard deviation of additive noise. The ICI algorithm tracks the intersection of consecutive confidence intervals so that [8, 9]:

$$\underline{U_n}(i,j,k) \geq \overline{L_n}(i,j,k), \tag{3}$$

where $\underline{U_n}(i,j,k)$ and $\overline{L_n}(i,j,k)$ are:

$$\underline{U_n}(i,j,k) = \min_{m=1,\ldots,n}(U_m(i,j,k)), \tag{4}$$

$$\overline{L_n}(i,j,k) \geq \max_{m=1,\ldots,n}(L_m(i,j,k)). \tag{5}$$

The term $\sqrt{n}$ in the denominator of Eqs. (1) and (2) causes each of the following confidence interval to be narrower than the preceding one. Furthermore, the confidence interval width is also controlled by the coefficient of confidence z_c [4, 8]. Larger values of z_c give wider confidence intervals, resulting in oversized filter supports, while smaller z_c values result in narrower confidence intervals and undersized filter supports [4, 8]. The undersized filter supports decrease estimation bias and increase the variance, while the oversized filter supports result in large estimation bias, reducing the variance, as shown in [8, 10]. Thus, the estimation performance is significantly enhanced by the proper z_c value (the proper filter support size selection). The largest n for which Eq. (3) is satisfied is shown to define the proper filter support size which minimizes the estimation error [8, 10].

3. THE ALGORITHM FOR VIDEO DENOISING

The algorithm takes a pixel from the first frame of a noisy video signal and calculates the corresponding upper and lower confidence intervals limits $U_n(i,j,1)$ and $L_n(i,j,1)$, where $\overline{X}_1(i,j,1)$ for the first frame is denoted as $x(i,j,1)$.

Subsequently, the second confidence interval to the right is calculated, for which $\overline{X}_2(i,j,1)$ is $(x(i,j,1)+x(i,j,2))/2$. If there exists the intersection of the first two confidence intervals, (Eq. (3) is satisfied), the algorithm moves to the next confidence interval to the right hand side for which $\overline{X}_3(i,j,1)$ is $(x(i,j,1)+x(i,j,2)+x(i,j,3))/3$. The algorithm then checks the existence of intersection of all three confidence intervals. If this intersection is a non-empty set, it continues on to the next confidence interval calculation. However, if Eq. (3) is not satisfied for those three confidence intervals, the algorithm sets $n_r^*(i,j,1)$ to 2 ($n_r^*(i,j,1)$ is defined as the largest $n_r(i,j,1)$ for which Eq. (3) is satisfied).

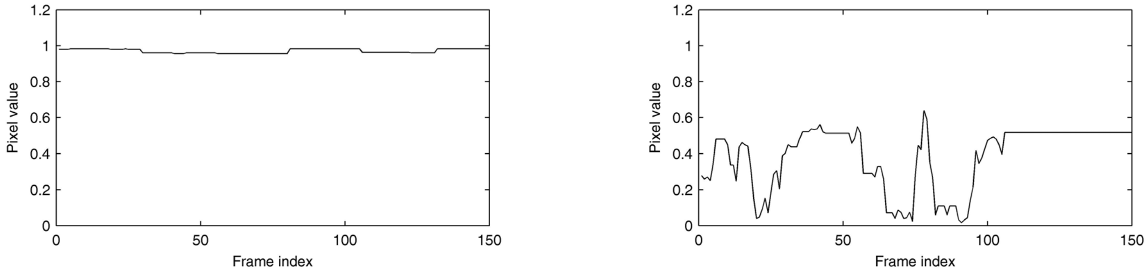
The same procedure is performed for the left hand side, resulting in $n_l^*(i,j,1)$ as the largest $n_l(i,j,1)$ for which Eq. (3) is satisfied. The estimated pixel value $\hat{x}(i,j,1)$ is calculated as the mean value of all $x(i,j,1)$ for which its accompanying confidence intervals intersect:

$$\hat{x}(i,j,1) = \frac{x(i,j,1-n_l^*(i,j,1)) + \cdots + x(i,j,1+n_r^*(i,j,1))}{n_l^*(i,j,1)+n_r^*(i,j,1)+1}. \tag{6}$$

The above procedure is repeated for each frame pixel and each video frame independently, resulting in a noise-free video signal estimate $\hat{x}(i,j,n)$.

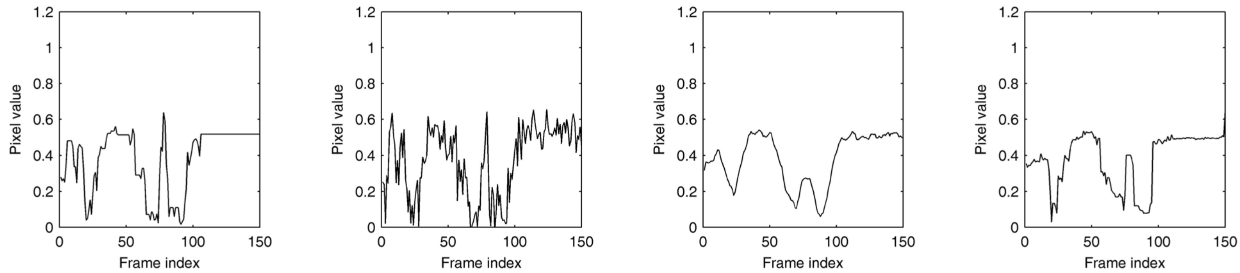
4. THE EXPERIMENTAL RESULTS

The proposed video denoising method's performance, measured as the average frame peak signal-to-noise ratio (PSNR), is analyzed on three test videos signals obtained by recording moving objects.



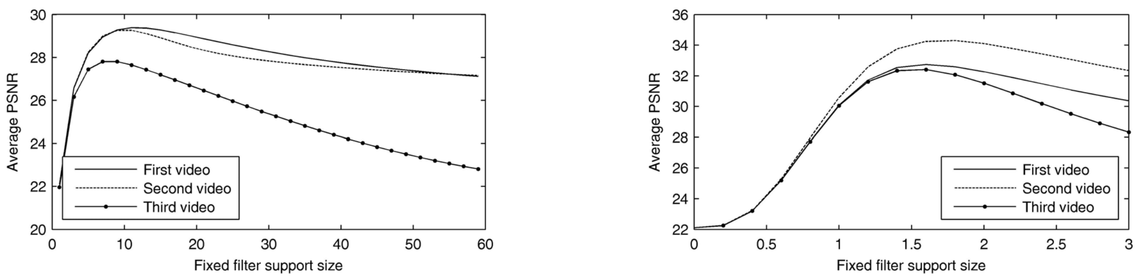
(a) (b)

Figure 1 Video pixel value over time. (a). Stationary video segment. (b) Video segment showing a moving object.



(a) (b) (c) (d)

Figure 2 Video pixel value over time from a video segment showing a moving object. (a) Noise-free video. (b) Noisy video (additive white Gaussian noise with $\sigma = 20$).(c) Denoised video using the fixed size filter support based method. (d) Denoised video using the ICI rule based method (z_c = 1.7).



(a) (b)

Figure 3 (a) Average frame PSNR of denoised videos for a range of fixed size filter supports ($\sigma = 20$). (b) Average frame PSNR of denoised videos for a range of z_c values ($\sigma = 20$).

Examples of video pixel value over time from both a stationary video segment and a video segment showing a moving object are given in Fig. 1. Fig. 2 shows examples of video pixel from a video segment of a moving object from a noise-free video, noisy video and a video denoised by using the fixed size filter support based method and the adaptive method based on the ICI rule presented in this paper, respectively.

As in [11], the fixed filter support size was chosen to be 11 and the ICI based method parameter z_c value was set to z_c = 1.7 due to the fact that those values result in the maximum average frame PSNR for the considered test videos, as shown in Fig. 3.

The noise-free video frame from the first test video is given in Fig. 4(a). The noisy video frame shown in Fig. 4(b) is corrupted by additive white Gaussian noise of $\sigma = 20$. Figs. 4(c) and 4(d) show the denoised video frame obtained by using the fixed size filter support based method and the ICI rule based method, respectively.

Fig. 4(d) illustrates the fact that the proposed method based on the ICI rule has significantly suppressed the noise present in the video signal, while the moving object has not been blurred and its edges have been well preserved. However, that is not the case for the video signal denoised using the fixed size filter support based method.

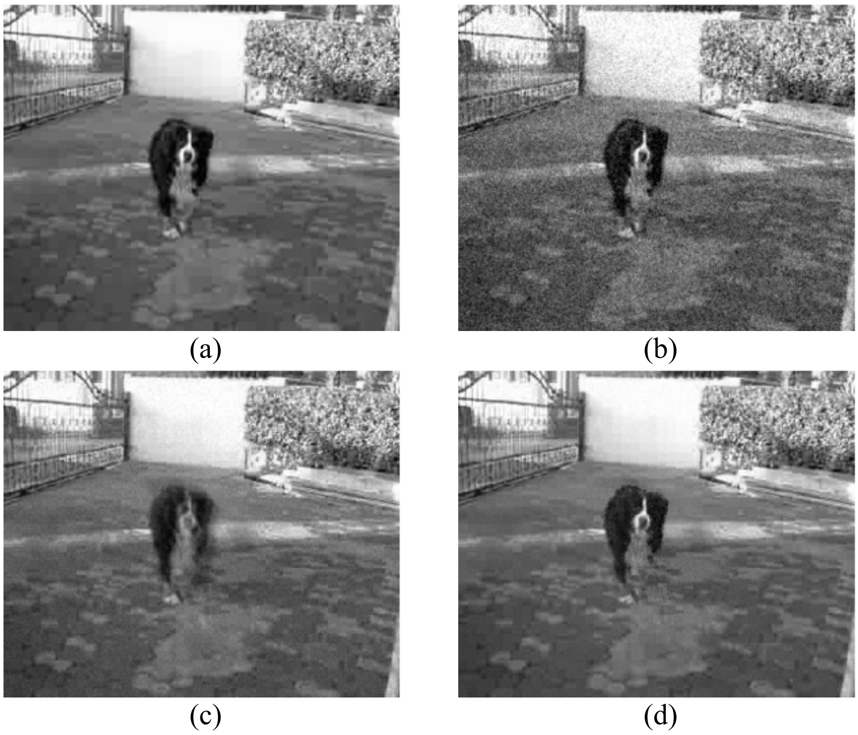


Figure 4. Video denoising results for the first test video. (a) Noise-free video frame. (b) Noisy video frame (additive white Gaussian noise with $\sigma = 20$). (c) Frame from video denoised using the method based on the fixed size filter support. (d) Frame from the video denoised using the ICI based method (z_c = 1.7).

Table 1. Average frame PSNR for the first test video denoised using the fixed filter support size based method and the adaptive method based on the ICI rule

	Average frame PSNR		
σ	Noisy video	Video denoised using the ICI rule $z_c = 1.7$	Video denoised using the fixed filter support size based method
1	48.13	**53.95**	32.38
2	42.08	**48.58**	32.34
5	34.12	**41.95**	32.14
10	28.16	**37.35**	31.45
15	24.60	**34.73**	30.48
20	22.15	**32.86**	29.45
25	20.19	**31.38**	28.38
30	18.57	**30.22**	27.36
50	14.17	**26.78**	23.89
100	8.13	**22.56**	18.35

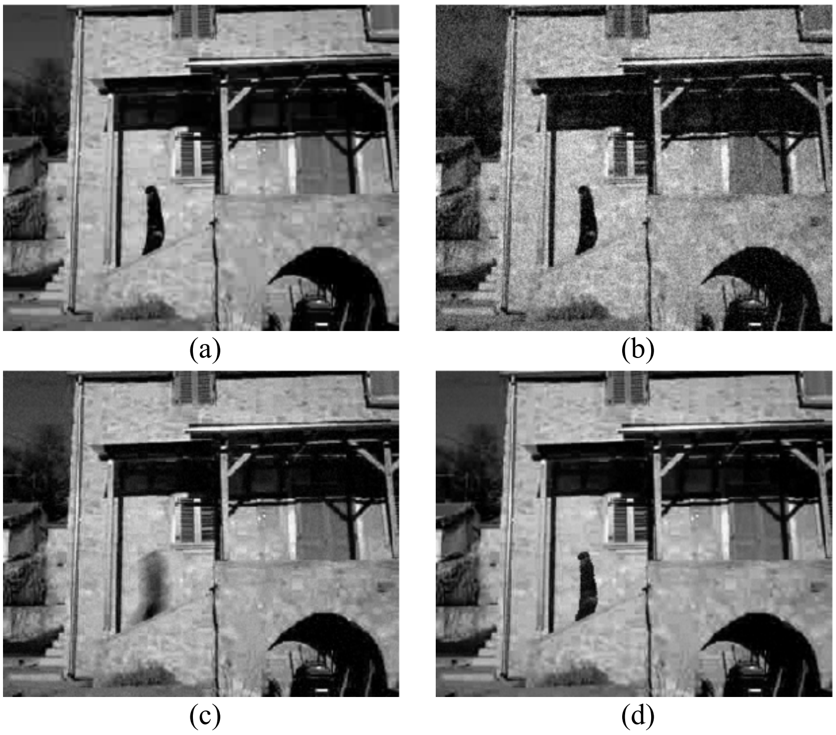


Figure 5 Video denoising results for the second test video. (a) Noise-free video frame. (b) Noisy video frame (additive white Gaussian noise with $\sigma = 20$). (c) Frame from video denoised using the method based on the fixed size filter support. (d) Frame from the video denoised using the ICI based method (z_c = 1.7).

Table 2 Average frame PSNR for the second test video denoised using the fixed filter support size based method and the adaptive method based on the ICI rule

	Average frame PSNR		
σ	Noisy video	Video denoised using the ICI rule z_c = 1.7	Video denoised using the fixed filter support size based method
1	48.12	**53.53**	30.74
2	42.13	**47.62**	30.72
5	34.14	**41.74**	30.58
10	28.12	**38.13**	30.07
15	24.59	**35.92**	29.40
20	22.15	**34.44**	28.55
25	20.16	**33.12**	27.68
30	18.57	**32.02**	26.77
50	14.14	**27.92**	23.63
100	8.12	**22.76**	18.30

The average frame PSNR for the video denoised using the ICI method is improved by 10.71 dB (the noisy video average frame PSNR is 22.15 dB, while the average frame PSNR of the video denoised using the ICI rule based method is 32.86 dB). The obtained improvement in the average frame PSNR using the adaptive ICI based method for the first test video, when compared to the average frame PSNR obtained by using the fixed size filter support based method, is 3.41 dB.

The denoising results for a range of noise levels are given in Table 1 both for the fixed size filter support based method and the adaptive method based on the ICI rule. The first column of Table 1 gives the standard deviations of additive white Gaussian noise.

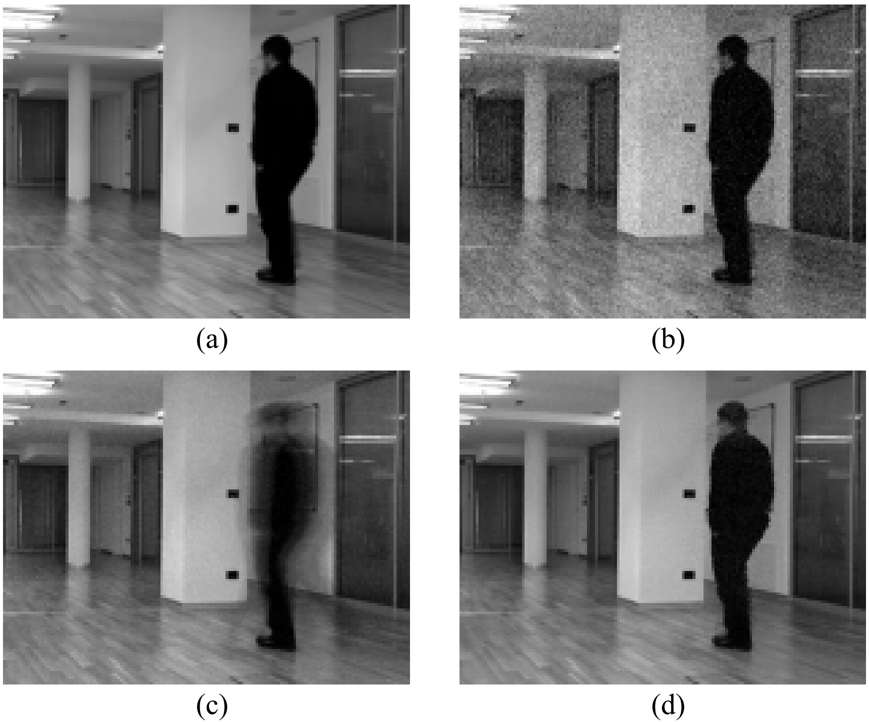


Figure 6 Video denoising results for the third test video. (a) Noise-free video frame. (b) Noisy video frame (additive white Gaussian noise with $\sigma = 20$). (c) Frame from video denoised using the method based on the fixed size filter support. (d) Frame from the video denoised using the ICI based method (z_c = 1.7).

Table 3 Average frame PSNR for the third test video denoised using the fixed filter support size based method and the adaptive method based on the ICI rule

	Average frame PSNR		
σ	Noisy video	Video denoised using the ICI rule $z_c = 1.7$	Video denoised using the fixed filter support size based method
1	48.13	**49.77**	26.03
2	42.10	**45.92**	26.02
5	34.13	**40.62**	25.97
10	28.14	**36.31**	25.79
15	24.60	**33.84**	25.53
20	22.08	**31.51**	25.19
25	20.19	**29.58**	24.75
30	18.57	**27.90**	24.26
50	14.14	**23.48**	22.23
100	8.19	**19.01**	17.84

The second column gives the average frame PSNR values for the noisy video, while the third and the fourth column present the average frame PSNRs obtained for the video denoised by using the ICI based method with $z_c = 1.7$ and the fixed size filter support based method, respectively.

As it can be seen from Table 1, the adaptive ICI base method increased the average frame PSNR by up to 14.64 dB when compared to the noisy video signal and by up to 22.76 when compared to the denoised video signal obtained by using the fixed size filter support based method.

A noise-free video frame from the second test video is given in Fig. 5(a). The video frame shown in Fig. 5(b) is corrupted by additive white Gaussian noise with $\sigma = 20$, while Fig. 5(c) and Fig. 5(d) show the denoised video frame obtained by using the fixed size filter support based method and the adaptive method based on the ICI rule ($z_c = 1.7$), respectively.

The adaptive method based on the ICI rule improved the average frame PSNR value of the denoised video by 12.29 dB (the noisy video average frame PSNR is 22.15 dB, while the average frame PSNR of video denoised using the ICI rule based method is 34.44 dB). When compared to the average frame PSNR obtained by using the fixed size filter support based method, the obtained improvement for the second test video using the adaptive ICI based method is 5.89 dB.

In comparison with the first test video, the adaptive ICI based method has also preserved the moving object edges without blurring them in the second test video.

As it can be seen from Table 2, the adaptive ICI base method increased the average frame PSNR by up to 22.76 when compared to the denoised video signal obtained with the fixed size filter support based method and by up to 14.64 dB when compared to the noisy video signal.

Fig. 6(a) shows the noise-free video frame from the third test video signal. Fig. 6(b) shows a frame from the video signal corrupted by additive white Gaussian noise. Fig. 6(c) and Fig. 6(d) present the denoised video frames obtained by using the fixed filter support size based method and the adaptive method based on the ICI rule, respectively.

Using the adaptive ICI based method (as it can be seen in Fig. 6(d)), the video denoising method has improved the average frame PSNR by 9.43 dB (the noisy average frame PSNR is 22.08 dB, while the denoised frame PSNR using the ICI rule based method is 31.51 dB). The average frame PSNR obtained by using the fixed size filter support based method has increased by 6.32 dB in comparison to the average frame PSNR obtained by the ICI based method for the third test video.

The adaptive ICI based method has preserved the moving object edges without blurring them. The method, as shown in Table 3, has increased the average frame PSNR by up to 23.74 dB when compared to video signal denoised using the fixed size filter support based method and by up to 14.64 dB when compared to the noisy video signal average frame PSNR.

As it can bee seen from Figs. 4(d), 5(d) and 6(d), the ICI based method, unlike the fixed size filter support based method, is suitable for denoising videos recording both stationary scenes and videos with changes in the recording scene (recording moving objects), which are far more often encountered in practical applications.

5. CONCLUSION

This paper has presented the adaptive video denoising method based on the ICI rule. The method has been applied to three real-life video signals and compared to the fixed size filter support based method. The method results in the average frame PSNR improvement of 23.74 dB when compared to the fixed size filter support based method, and 14.64 dB when compared to the average frame PSNR of the noisy video signal. Unlike the fixed size filter support based method, the adaptive method based on the ICI rule is shown to be efficient in recording object edge preserving, while at the same time avoiding its blurring. Thus, the ICI based method, unlike the fixed size filter support based method, is not limited only to the video signal obtained by recording stationary scenes, but it can be also successfully applied to video signals recording moving objects, which are to be far more often encountered in practice.

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