

# An ICI Based Algorithm for Fast Denoising of Video Signals

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In this paper, we have proposed a fast method for video denoising using the modified intersection of confidence intervals (ICI) rule, called fast ICI (FICI) method. The goal of the new FICI based video denoising method is to maintain an acceptable quality level of the denoised video estimate, and at the same time to significantly reduce denoising execution time when compared to the original ICI based method. The methods are tested on real-life video signals and their performances are analyzed and compared.

It is shown that the FICI method outperforms the ICI method in terms of the execution time reduction by up to 96% (or up to 25 times). However, practical application demands dictate the choice of the video denoising method. If one wants fast denoising method with decent denoising results, the FICI based video denoising method is a better choice. The original ICI method, however, should be used in applications where significant noise suppression is an imperative regardless the computational complexity.

**Key words:** adaptive and temporal filtering, edge preserving, intersection of confidence intervals (ICI) rule, video denoising

**Algoritam za brzo uklanjanje šuma iz video signala temeljen na ICI postupku.** U ovom smo radu predložili brzi postupak za uklanjanje šuma iz video signala koristeći modificirano pravilo presjecišta intervala pouzdanosti (eng. intersection of confidence intervals - ICI), nazvano brzim ICI (eng. fast ICI – FICI) postupkom. Cilj novog FICI postupka za uklanjanje šuma iz video signala jest da se, uz zadržavanje prihvatljive razine kvalitete odšumljenog video signala, značajno smanji vrijeme izvršavanja algoritma u usporedbi s izvornim ICI postupkom. Postupci su testirani na realnim video signalima, a njihove su performanse analizirane i uspoređene.

Pokazano je da FICI postupak ima do 96% kraće vrijeme izvršavanja (odnosno kraće i do 25 puta) u uspoređi s izvornim ICI postupkom. Međutim, zahtjevi praktične primjene određuju izbor postupka za uklanjanje šuma iz video signala. Ukoliko je potrebno brzo izvršavanje s pristojnim performansama uklanjanja šuma, FICI postupak je bolji izbor. Međutim, u aplikacijama kojima je imperativ značajno suzbijanje šuma bez obzira na računsku složenost, trebao bi se koristiti izvorni ICI postupak.

**Ključne riječi:** adaptivno i vremensko filtriranje, očuvanje rubova, metoda presjecišta intervala pouzdanosti, uklanjanje šuma iz video signala

## 1 INTRODUCTION

Real-life digital data sets are often contaminated by noise, either because of the data acquisition process or because of a naturally occurring phenomena [1]. In order to obtain the best possible estimate from noisy data, a robust, efficient and reliable denoising method is required. Various denoising methods have been proposed in the last few decades, a review of which can be found in [2], where their features are elaborated and compared.

In this paper, a video denoising method based on the intersection of confidence intervals (ICI) rule is presented [3, 4, 5]. The ICI rule is an automatic adaptive procedure for selecting the appropriate adaptive filter support size for

each pixel in each video frame in order to obtain a denoised video with minimal estimation error [6]. The modified ICI rule, called the Fast ICI (FICI) method, applied to video denoising is proposed in this paper. Its main goal is to maintain acceptable quality level of the denoised video estimate, and at the same time to significantly reduce denoising algorithm execution time when compared to the original ICI based method. The two video denoising methods are tested on real-life video signals, and their characteristics are analyzed and compared.

The paper is organized as follows. In Section 2, the ICI algorithm is briefly outlined, while in Section 3 the new modified ICI based method (FICI method) is introduced. Section 4 gives experimental denoising results for

test videos also providing the methods' denoising quality and time performance analysis. The conclusion is given in Section 5.

## 2 THE ICI METHOD

Let us consider a noisy video pixel  $x(i, j, k)$  and the corresponding noise free video pixel  $\hat{x}(i, j, k)$ , where  $i$  and  $j$  are the pixel indices and  $k$  stands for the video frame index. The absolute estimation error can be calculated as

$$|e(i, j, k, h)| = |\tilde{x}(i, j, k) - \hat{x}(i, j, k, h)| \quad (1)$$

where  $\hat{x}(i, j, k, h)$  is the estimated noise free video pixel, obtained using the filter support size  $h$ .

As shown in [7], the absolute estimation error is

$$|e(i, j, k, h)| \leq |\bar{m}_e(i, j, k, h)| + |e^0(i, j, k, h)| \quad (2)$$

where  $|\bar{m}_e(i, j, k, h)|$  is the maximum value of the estimation bias and  $|e^0(i, j, k, h)|$  is random error with probability density  $N(0, \sigma_x^2(i, j, k, h))$ .

It was shown in [7] that the following inequality

$$|e^0(i, j, k, h)| \leq \chi_{1-\alpha/2} \cdot \sigma_x(i, j, k, h) \quad (3)$$

holds with probability  $1 - \alpha$ , where  $\chi_{1-\alpha/2}$  is  $(1 - \alpha/2)$ -th quantile of the standard Gaussian distribution and  $\sigma_x(i, j, k, h)$  is the standard deviation of noise.

Furthermore, as shown in [7], the following inequality holds true with the same probability  $1 - \alpha$

$$|e(i, j, k, h)| \leq |\bar{m}_e(i, j, k, h)| + \chi_{1-\alpha/2} \cdot \sigma_x(i, j, k, h) \quad (4)$$

and can be reduced to

$$|e(i, j, k, h)| \leq z_c \cdot \sigma_x(i, j, k, h) \quad (5)$$

for  $h \leq h^*(i, j, k)$ , where  $h^*(i, j, k)$  is the optimal filter support size for the considered pixel  $x(i, j, k)$ , and  $z_c$  is the coefficient of confidence.

The adaptive filter support selection procedure based on the ICI rule introduces a finite set of filter support sizes and calculates a sequence of confidence intervals limits of the biased estimates for each video frame pixel separately and independently to its left and right hand side. The confidence intervals limits of confidence intervals for one side (for instance right hand side) are computed as [4]:

$$U_n(i, j, k) = \hat{x}_n(i, j, k) + z_c \frac{\sigma_x}{\sqrt{n}} \quad (6)$$

$$L_n(i, j, k) = \hat{x}_n(i, j, k) - z_c \frac{\sigma_x}{\sqrt{n}} \quad (7)$$

where  $U_n(i, j, k)$  is upper and  $L_n(i, j, k)$  is lower confidence interval limit while  $\hat{x}_n(i, j, k)$  represents estimated

value of the considered video pixels. As it can be seen from (6) and (7), each following confidence interval is narrower than the preceding one. Following the intervals computation, their intersections are being tracked with respect to the following equation [8, 9]

$$\max_{n=1, \dots, N-k+1} (L_n(i, j, k)) \leq \min_{n=1, \dots, N-k+1} (U_n(i, j, k)). \quad (8)$$

The largest  $n$  for which (8) is satisfied was shown to define the proper filter support size which minimizes the estimation error [8, 10]. The same procedure is repeated for the left hand side of the considered pixel  $x(i, j, k)$ . Once the right and left hand side time regions are calculated for considered  $x(i, j, k)$ , they are combined and used in noise free  $\hat{x}(i, j, k, h)$  estimation.

The coefficient of confidence  $z_c$  plays an important role in confidence intervals calculating and denoising efficiency [8, 10]. Too small values of  $z_c$  increase variance and decrease estimation bias resulting in undersized filter supports [8, 10]. On the other hand, too large  $z_c$  values reduce variance and increase estimation bias resulting in oversized filter supports [8, 10]. The proper  $z_c$  value selection procedure is given in [11].

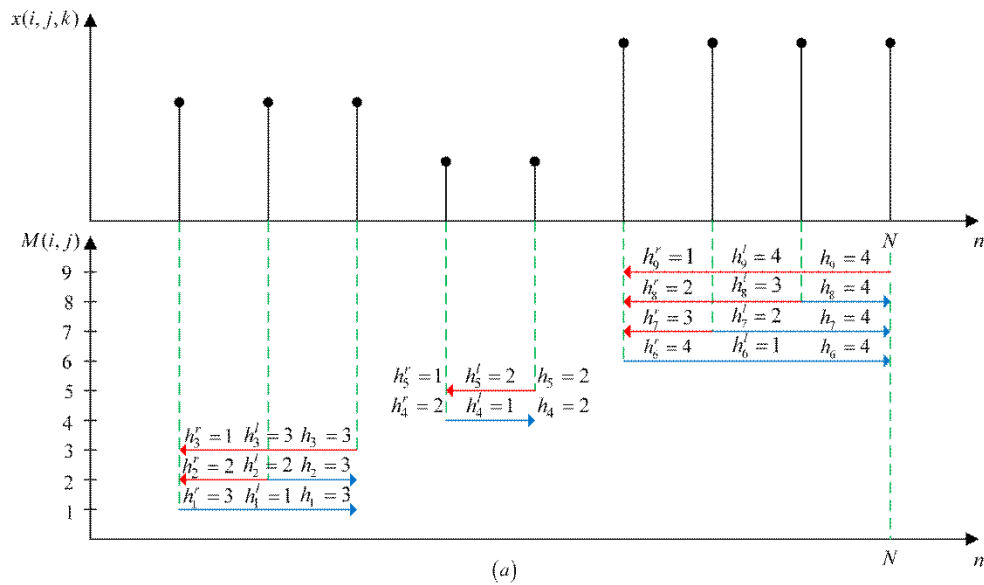
Once the filter support size is detected using the ICI method, the noise free video estimate is calculated using all video pixels in time region neighboring the considered video pixel  $x(i, j, k)$ . A simple way to estimate noise free video pixel is by averaging the pixel values in the region or to find its medium value in case of impulse noise. The comparison of the results obtained using the mean and median filtering is given in Section 4.

The modification of the original ICI based method in order to speed up its execution is given in the next Section.

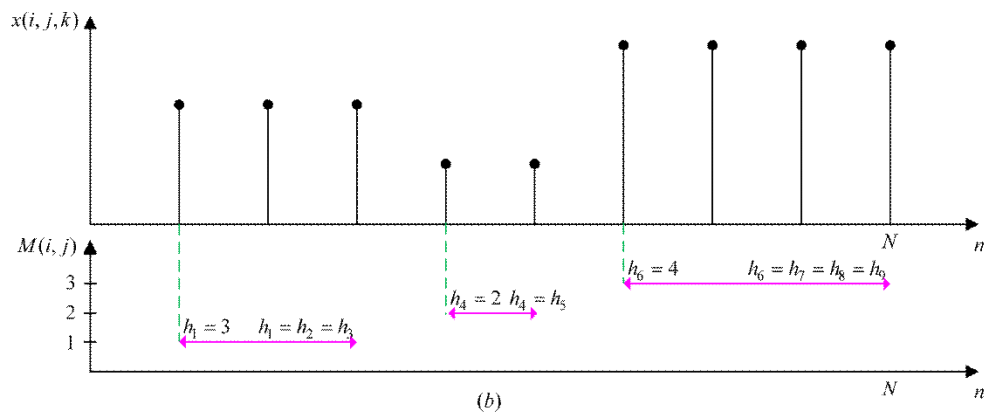
## 3 THE FAST ICI (FICI) METHOD

Since video denoising using the original ICI based method is rather time consuming, in order to speed up the denoising process a modified ICI method (here named FICI method) is proposed. The goal of the FICI method is to maintain acceptable quality level of the noise free video estimate while significantly reducing denoising execution time when compared to the original ICI method.

Unlike the ICI based method, the FICI method does not calculate filter support sizes for each video pixel in each frame, but rather detects appropriate time regions for each pixel in time, as shown in Fig. 1. It calculates the filter support size for the first pixel value in the detected time region applying the same filter support size to all estimated noise free pixel values in the detected time region. Thus, the accurate time region selection (controlled by parameter  $z_c$ ) plays a key role in video denoising quality. Various methods for proper parameter  $z_c$  value selection were proposed



(a) The ICI based filter support size calculation (the number of filter supports calculated is the same as the number of samples in the signal).



(b) The FICI based filter support size calculation (a significantly reduced number of filter supports calculated, hence significant algorithm execution time reduction is obtained).

Fig. 1. An example of filter support size calculation using the ICI and FICI method

over the last few decades, such as the method based on cross-validation which was proven to be a good criterion for selection of this data-driven threshold resulting in estimation accuracy improvement [10].

For the considered noisy video pixel in time  $x(i, j, k)$  the confidence intervals limits and their intersections are computed using the same equations for the FICI method as for the ICI method ((6), (7) and (8)). Due to the fact that the adaptive support filter size is calculated only for the first pixel value in the detected time region the modified ICI method computes confidence intervals limits only to the right hand side for each video pixel in time, while the original ICI based method requires both left hand and right hand side calculation of confidence interval and left

hand and right hand side tracking of intersection of confidence intervals in order to find the filter support size for the considered pixel.

The FICI based denoising algorithm starts by considering the varying of video pixel value in time, denoted as  $x(i, j, k)$  (where  $k = 1, 2, \dots, N$ , and  $N$  is the total number of video frames), and calculates its upper and lower confidence interval limits for each  $k$  as long as (8) is satisfied. The largest filter support size for which (8) is satisfied, denoted as  $h_1(i, j)$ , is then added to the filter support size set  $H(i, j)$  for the considered video pixel.

If  $h_1 \neq N$ , the above procedure is repeated for  $x(1, 1, h_1 + 1)$ , resulting in  $h_2(i, j)$ , also added to the filter support size set  $H(i, j)$ .

The procedure is repeated until  $\sum_{n=1}^{M(i,j)} h_n = N$  where  $M(i, j)$  is the number of detected time regions for the considered pixel in time.

Unlike the original ICI based method, where confidence intervals and their intersections are calculated for each frame pixel up to  $N$  times, here proposed FICI method reduced their calculation to  $M(i, j)$  times,  $1 \leq M(i, j) \leq N$ , leading to significant reduction of the computational and memory demands. In case of the image background pixel when the  $M(i, j)$  is smaller then for the pixel showing moving object, reduction in the execution time and memory demands becomes even more notable.

Thus, for the pixel  $x(i, j, k)$ , the FICI method provides filter support size set defined as

$$H(i, j) = [h_1, \dots, h_n, \dots, h_{M(i,j)}], \sum_{n=1}^{M(i,j)} h_n = N \quad (9)$$

and time regions starting points set  $K(i, j)$ , defined as

$$K(i, j) = [k_1=1, k_2=1+h_1, \dots, k_n=(1+h_1+\dots+h_{n-1})]. \quad (10)$$

Once the filter support size is calculated using the FICI rule, the noise-free estimates can be obtained by applying the mean filtering

$$\hat{x}_{mean}(i, j, k) = \frac{1}{h_n} \sum_{z=k_n}^{k_{n+1}-1} x(i, j, z), k_n \leq k < k_{n+1}-1, \quad (11)$$

or median filtering

$$\hat{x}_{median}(i, j, k) = median(x(i, j, k_n), \dots, x(i, j, k_{n+1}-1)), k_n \leq k < k_{n+1}-1. \quad (12)$$

to all pixels in the calculated time region.

The above procedure is repeated for each pixel in the video signal, resulting in noise-free video estimate.

#### 4 RESULTS

Performances of the presented video denoising algorithms are analyzed for two test videos. The videos are obtained by recording a moving object passing through a stationary scene. The average frame peak signal-to-noise ratio (PSNR) was used as a measure of video estimation quality (obtained by averaging all frame PSNRs of the denoised videos). Note that other image quality measures can be used for describing visual effects in denoised video, such as the wavelet based measure which provides improved correlation with subjective grades of image quality [13].

Examples of a video pixel varying in time for the noise free, noisy and denoised videos are shown in Fig. 2.

Table 1. Average frame PSNR values for the first test video denoised using both the ICI and the FICI method for a range of noise levels.

Average frame PSNR				
Noisy video	Denoised video, $z_c = 1.9$			
	ICI		Fast ICI	
	Mean	Median	Mean	Median
34.20	40.20	39.50	38.86	38.29
28.15	36.17	35.85	33.11	32.50
24.64	33.19	33.48	29.42	28.58
22.15	31.06	31.36	26.74	26.00
20.23	29.17	29.56	25.07	24.40
18.59	27.42	27.86	23.70	22.86
17.25	26.04	26.21	22.62	21.79
16.13	24.85	24.67	21.72	20.80
15.08	23.73	23.44	21.05	20.17
14.20	22.80	22.29	20.52	19.65

The coefficient of confidence  $z_c$  was chosen to be 1.9 for both test videos. Its selection is justified in Fig. 3 where it can be seen that denoising using the selected  $z_c$  value results in denoised video estimates with largest average frame PSNR.

The first test video is composed of 150 video frames, recorded using 25 frames per second. The resolution of the video is  $320 \times 250$  pixels. The first noise free video frame, along with a noisy video frame corrupted by the impulse Poisson noise, are given in Figs. 4(a) and 4(b), respectively. Figs. 4(c) and 4(d) give the denoised video frames obtained using the ICI based method ( $z_c = 1.9$ ) after applying mean and median filtering, respectively. Figs. 4(e) and 4(f) give the denoised frames obtained by the FICI method ( $z_c = 1.9$ ) using mean and median filtering, respectively.

As it can be seen from Figs. 4(c) and 4(d), the method based on the ICI rule has significantly suppressed the noise present in the video signal, the moving object has not been blurred and its edges are well preserved. The average frame PSNR is improved by up to 8.02 dB when compared to the noisy video the frame of which is shown in Fig. 4(a) (average PSNR of noisy video is 28.15 dB), as it can be seen in Table 1. When compared to the results obtained using the FICI method, as shown in Figs. 4(e) and 4(f), the obtained average frame PSNR is somewhat smaller than the one obtained using the original ICI rule based method (the original ICI method increased the average frame PSNR by 8.02 dB when compared to the noisy video signal, while the FICI method increased the average frame PSNR by 4.96 dB). However, total execution time for denoising the whole video signal using the FICI based method was significantly reduced (by up to 95% or up to

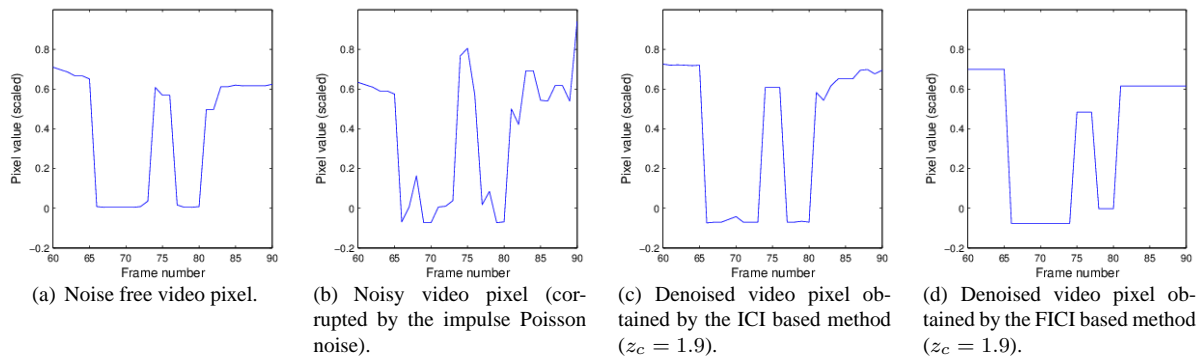
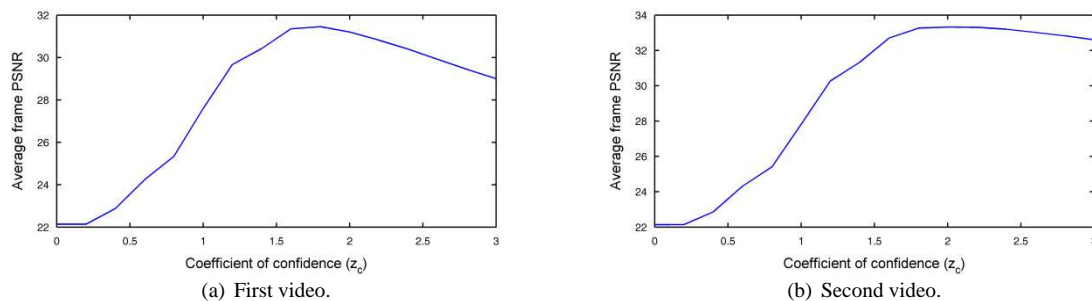


Fig. 2. Video pixel in time

Fig. 3. Average frame PSNR values with respect to the  $z_c$  parameter value obtained using the ICI based method.

21 times when compared to the original ICI method).

Tables 3 and 4 give the total execution time needed for complete video denoising both for the ICI and the FICI based method, as well as for the mean and median filtering for both test videos, respectively. Note that the choice of the filtering method does not significantly impact the total execution time since average time difference between mean and median filtering is negligible. For measuring execution time performance Toshiba A660 notebook powered by Intel®Core™ i5 CPU M 430 @ 2.27 GHz with 4 GiB of RAM was used.

The choice of video denoising method in practical applications depends on application demands. For a fast denoising method with decent denoising results the FICI method is a far better choice than the original ICI method which should be used in applications requiring noise to be suppressed as much as possible. However, when compared to the fixed filter support size based methods, the results obtained using the FICI method are far more reliable and denoised video estimation quality is significantly improved (fixed filter support size based methods show low performance in denoising videos with changes in the recording scene, as shown in [6, 12]).

Table 1 gives the first test video denoising results for mean and median filtering both for the ICI and the FICI

based method. There is a very small difference in the denoised video average frame PSNR obtained by mean and median filtering. When comparing Figs. 4(c) and 4(d), obtained by the ICI based method no significant visual difference is noticed. The same stands for Figs. 4(e) and 4(f) obtained by the FICI based method. The first column of Table 1 gives the average frame PSNRs for the noisy video, while the second and the third column present the average frame PSNRs for the video denoised using the ICI based method ( $z_c = 1.9$ ) for mean and median filtering, respectively. The fourth and the fifth column present the average frame PSNRs obtained for the video denoised using the FICI based method ( $z_c = 1.9$ ) for mean and median filtering, respectively. The original ICI method has increased the average frame PSNR by up to 9.33 dB when compared to all noisy video signals, while the FICI method has increased the average frame PSNR by up to 6.32 dB (also considering all noise levels of noisy video signals), as shown in Table 1.

The second test video is composed of 150 video frames recorded using 25 frames per second. The resolution of the test video is  $300 \times 245$  pixels. The noise-free video frame along with noisy frame corrupted by the impulse Poisson noise are given in Figs. 5(a) and 5(b), respectively. Figs. 5(c) and 5(d) show the denoised frames obtained by the

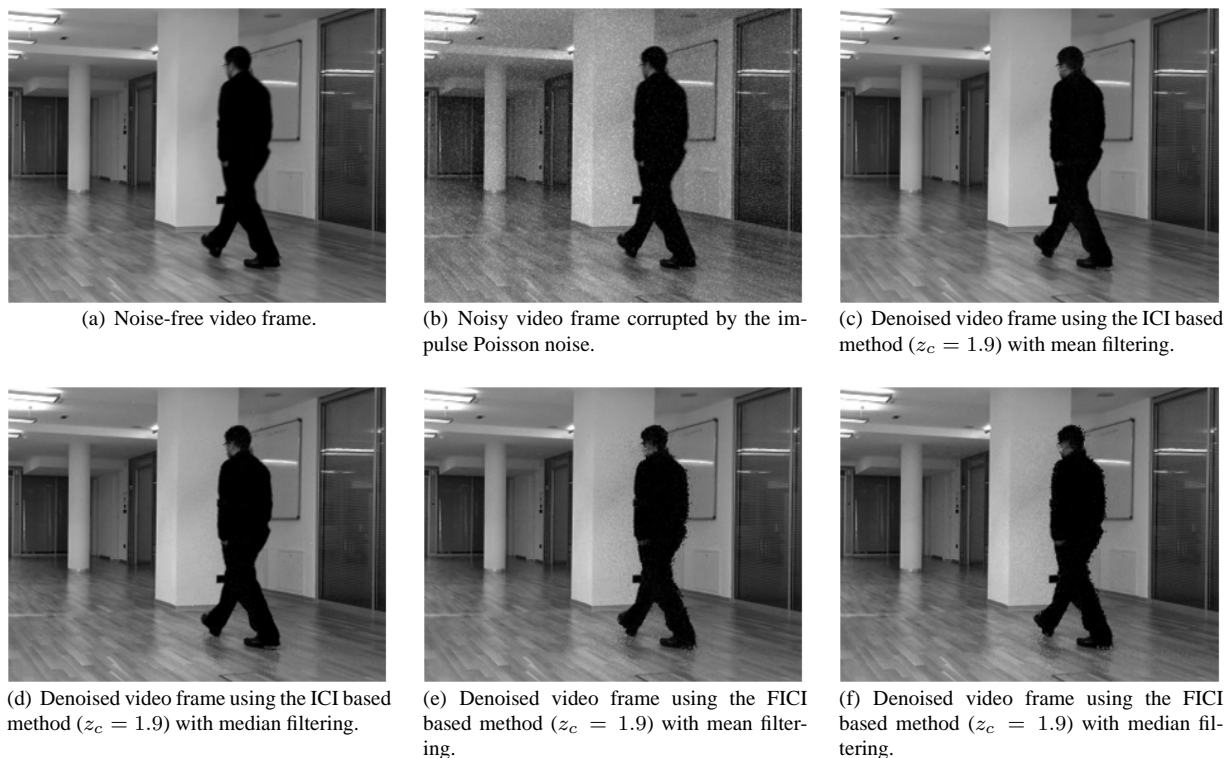


Fig. 4. First test video.

ICI based method using mean and median filtering, respectively, while Figs. 5(e) and 5(f) show the denoised frames for the FICI method using mean and median filtering, respectively.

As in the first test video, the proposed ICI based method has preserved the moving object edges without blurring them, as it can be seen in Figs. 5(c) and 5(d). The average frame PSNR was improved by 12.48 dB when compared to the noisy video the frame of which is shown in Fig. 5(a), as given in Table 2, achieving a significant noise suppression. The new FICI method has improved the average frame PSNR by 10.24 dB, as shown in Figs. 5(e) and 5(f). As for the first test video signal, the execution time was significantly reduced (by up to 96% or up to 25 times) when compared to the original ICI method.

The average frame PSNR comparison of mean and median filtering for second test video shows a very small PSNR difference between the two filtering methods, as given in Table 2. The adaptive ICI rule based method has increased the average frame PSNR by up to 14.11 dB when compared to all noisy video signals (all noise levels), while the FICI method has increased the average frame PSNR by up to 12.27 dB.

However, although the obtained average PSNR of denoised video using the FICI based method is somewhat

Table 2. Average frame PSNR values for the second test video denoised using the ICI and the FICI method for a range of noise levels.

Average frame PSNR				
Noisy video	Denoised video, $z_c = 1.9$			
	ICI		Fast ICI	
	Mean	Median	Mean	Median
34.20	41.67	41.07	41.08	40.12
28.15	37.92	36.88	37.31	36.07
24.64	35.77	34.74	34.65	33.23
22.15	34.63	33.40	32.39	31.10
20.23	33.45	32.44	30.75	29.26
18.59	32.20	31.44	29.69	27.97
17.25	31.00	30.17	28.59	26.93
16.13	29.77	29.50	27.83	26.21
15.08	29.13	28.26	27.16	25.57
14.20	28.31	27.31	26.47	24.67

smaller than the one obtained by the ICI based method, the execution time was reduced by up to 25 times.

This is the main advantage of the FICI based method, making it more appropriate for practical applications when one needs a fast denoising method with acceptable denois-

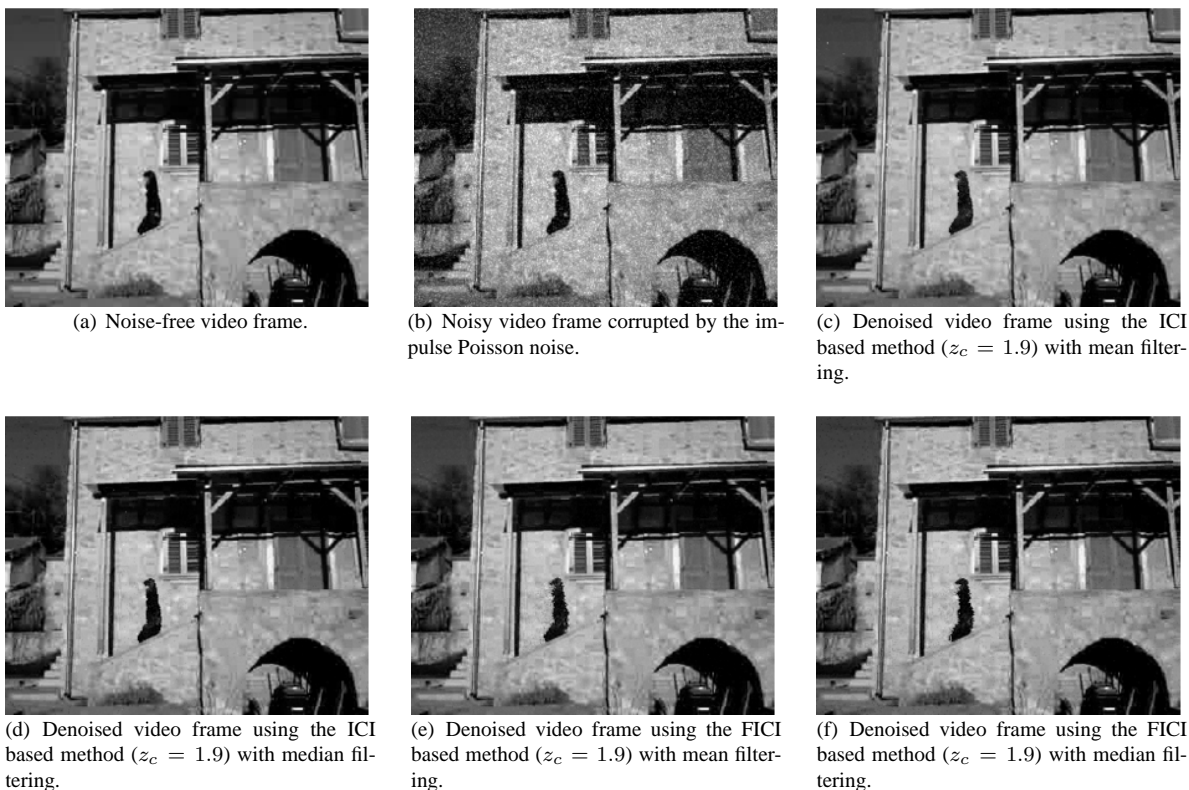


Fig. 5. Second test video.

ing quality.

Table 3. Execution time for the ICI and proposed FICI based methods for the first test video

Execution time in minutes			
ICI		Fast ICI	
Mean	Median	Mean	Median
158	159.38	7.85	7.61

Table 4. Execution time for the ICI and proposed FICI based methods for the second test video

Execution time in minutes			
ICI		Fast ICI	
Mean	Median	Mean	Median
124.26	127.45	4.95	5.17

Watching the videos denoised using the FICI method proves that the desired denoising results may be obtained by here proposed fast denoising method providing both well denoised background and the moving object, the contours/edges of which are also well preserved.

### 5 CONCLUSION

This paper has presented an adaptive video denoising method based on the novel modification of the ICI rule, here named the Fast ICI (FICI) method. The goal of the newly proposed method, which was successfully applied to video denoising, was to maintain acceptable quality of the denoised video estimate and at the same time significantly reduce denoising execution time when compared to the original ICI method. The method was tested on real-life video signals for which it has significantly outperformed the original ICI rule based method in terms of execution time, reducing it by up to 25 times. If one requires a fast denoising method with decent denoising results, the FICI based video denoising method is a better choice than the one based on the original ICI method, which, on the other hand, should be used in applications in which the execution time is not a limiting factor.

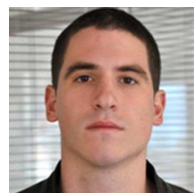
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