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Performance evaluation of noise reduction filters on electron beam images

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ABSTRACT

Digital image processing is now increasingly being used in electron accelerators to characterize electron beam. Measurement of electron beam parameters like beam size, beam centroid with high accuracy is required to optimize accelerator performance. Measurement accuracy of these parameters using digital image processing is limited by the noise present in the images. Reduction of noise without altering the features present in the image is a desired goal of image processing. In this paper we evaluate the noise reduction capability of median, mean, gaussian and wiener filters from digital images of electron beam image. The images were collected from Transport Line-1 in Indus Accelerator Complex at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, India. We also evaluate the effect of these filters on the measurement accuracy of beam parameters like beam size and beam centroid. It has been observed that performance of median filter for noise reduction is better than mean, gaussian and wiener filter. Median filter also creates less distortion in beam size and centroid of the beam in comparison with other filters.

Introduction

Digital image processing refers to the process of extracting meaningful information from digital images. In scientific domain like laser and particle (for example electron and proton) accelerator research, usage of digital image processing is constantly increasing. In electron accelerator research, digital image processing is used to characterize electron beam [1] [2] [3]. Particle accelerators are used to accelerate elementary particles like electrons to high energy level. Particle accelerators are constructed as a dedicated source of synchrotron radiation [4]. At Raja Ramanna Centre for Advanced Technology Indore, India, two electron synchrotron radiation sources namely Indus-1 and Indus-2 (commonly known as Indus Accelerator Complex) have been commissioned and are now in regular operation. A 20 MeV microton is used to inject electron beam into booster synchrotron through Transport Line-1 (TL-1). The energy of electron beam is raised to 450 MeV in booster synchrotron for injection into Indus-1 ring and 550 MeV for injection into Indus-2 ring. Measurement of electron beam parameters like beam size, beam shape and beam centroid in electron accelerators are required to optimize the transmission of beam in transport lines. Measurement of above beam parameters starts with image being formed on a fluorescent screen made of chromium doped alumina ceramic screen. When electron beam strikes on the fluorescent screen, it emits visible radiation which is captured by a monochrome analog CCD camera (CCD model 127LH make WATEC). A commercially available 8-bit frame grabber card (National Instruments NI-1411) is used to convert analog video signal from CCD camera into digital format. A software written in Visual Basic is used to acquire image into computer and Matlab software is used to carry out analysis of acquired image. The captured image can be used to extract information of beam centriod and beam size of electron beam using digital image processing.

The measurement of electron beam centroid and beam size from accelerator beam images with high precision (few tens of microns) requires that noise present in the images should be removed in such a manner that noise reduction filters should minimally affect the details present in images. The main objective of noise removal filters is to reduce noise while preserving information present in the image. The nature of noise present in the captured images should be understood clearly before any measurement is carried out. This paper is organized as follows. Section II describes the nature of noise present in the beam images. In section III the effect of mean, gaussian, wiener and median noise reduction filters is discussed on the synthetic gaussian image added with noise present in accelerator beam images. Conclusion of this work is presented in section IV.

Noise in accelerator beam images

Noise can be defined as any unwanted component of signal. The noise contained in digital images may not be correlated with true image data contained in the image because it arises from the different noise sources rather than subject itself. Noise generally consists of discrete pixels that are significantly different in appearance than adjacent pixels. Noise can be caused by a wide range of sources, e.g. variations in the detector sensitivity, environmental variations (like change in ambient temperature), the discrete nature of radiation, transmission or quantization errors, etc [5]. Noise can also be introduced in images due to presence of ionizing radiation in synchrotron radiation sources. Radiation environment due to synchrotron radiation source is mainly due to bremsstrahlung radiation, produced as a result of the interaction of high energy electrons with structural materials or gas molecules within the vacuum chamber which can affect the CCD sensor. In a camera system, the ionizing damage causes increased surface generated dark current [6].

Generally noise in images can be classified as

Image independent noise

Image independent noise can be modeled by an additive model as shown in (1)

$$I_1(x,y) = S_1(x,y) + N_1(x,y) \qquad (1)$$

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Where $I_1(x, y)$ is the recorded image, $S_1(x, y)$ is true image and $N_1(x, y)$ is the noise at an arbitrary pixel position x and y. The amplifier noise caused primarily by Johnson–Nyquist noise (thermal noise) is independent at each pixel and independent of the signal intensity can be considered as image independent noise. The noise of a CCD detector is a combination of the read noise of the CCD chip, the combined noise of the detector electronics and the dark current noise.

Image dependent noise

Image dependent noise can be represented with a multiplicative or non-linear model as given in (2).

$$I_2(x, y) = S_2(x, y) * N_2(x, y) \quad (2)$$

Here $I_2(x, y)$ is the recorded image, $S_2(x, y)$ is true image and $N_2(x, y)$ is the noise. In electron accelerators, external illumination arrangement is usually provided to view grid marked on fluorescent screen. The gridlines are used to convert pixels information into practical units like millimeter etc. Sometimes due to non-uniform illumination arrangement, captured images are corrupted by noise which is usually random in nature. Fig. 1 shows the image of electron beam on fluorescent screen captured by an analog CCD camera at RRCAT. Image in fig. 1 is quite noisy and extraction of any useful beam feature like beam centroid or beam size is difficult. Fig. 2 shows the dark frame image. A dark frame is an image captured with the CCD sensor in the dark, essentially just an image of noise in an image sensor. Fig. 3 shows the image after dark frame image was subtracted from image in fig. 1. It can be observed from fig. 3 that image is still quite noisy. A large number of dark frame images were captured under identical conditions to understand the temporal noise. The camera system was fully covered with dark black cloth to avoid entering any stray light into the CCD sensor which can affect the measurement accuracy.

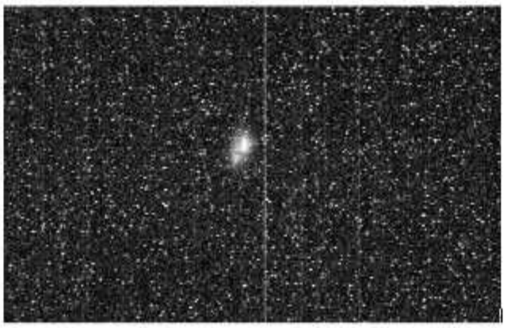

Figure 1. Electron beam image

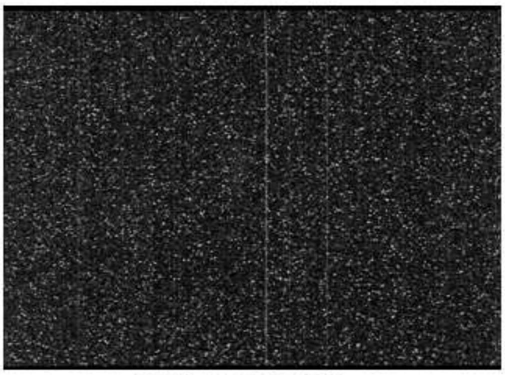

Figure 2. Dark frame image

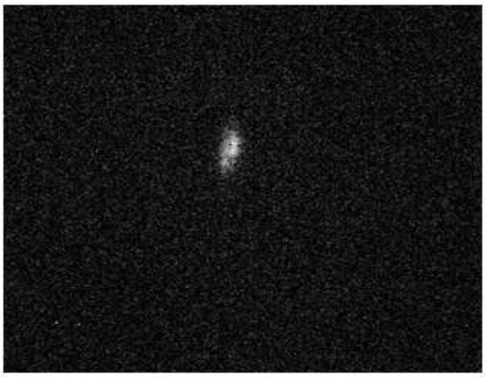

Figure 3. Electron beam image after dark frame subtraction

Analysis was carried out on the dark frame images using Matlab 7.9.0 software package. Analysis of dark frame images revealed that background noise is not fixed but random and it has two components viz fixed pattern noise and random noise. Fixed pattern noise present in images does not move or twinkle like normal noise. This noise is due to camera itself and same pattern is visible even when lens aperture is fully closed. This noise is due to two types of mismatch between the photo-signals; photo-signal generation mismatch and the photo-signal transportation mismatch. The photo signal mismatch is due to the variation of the pixels' photo-sensing areas, and to the mismatched dark currents. The dark current is the accumulation of electrical charge in the photodiode from electron-hole pairs that are generated independent of the photo-detection process. The primary sources of this are impurities or lattice defects in the silicon substrate. Because these defects are localized, the dark current is different for each pixel, leading to a fixed pattern noise in the image. The fixed pattern noise can be removed by subtracting dark frame image.

Simulation on synthetic image

In our study a synthetic symmetric gaussian image was created using (6) with zero mean and standard deviation (sigma) 141.4. The typical value of standard deviation was chosen to avoid saturation of pixel (maximum pixel value for 8 bit gray scale image is 255). The dark frame image was added to synthetic image. Fig. 4 shows the synthetic gaussian image. Fig. 5 shows synthetic gaussian image with added dark frame image noise.

We compared the effect of median filter, gaussian filter, wiener filter, mean filter for their effectiveness in removing the noise. A kernel of 3x3 pixel size was used in all filters. Median filter is a simple and powerful non-linear filter used for noise removal. Median filter is a spatial filter. The idea of median filtering is to replace each pixel value in an image with the median value of pixels in the window. The median is calculated by first sorting all the pixel values from the surrounding neighborhood (window) into numerical order and then replacing the pixel being considered with the middle pixel value. If the neighborhood under consideration contains an even number of pixels, the average of the two middle pixel values is used. The median filter is very effective at removing noise without destroying sharp edges in an image. The gaussian filter is a 2-D convolution operator that is used to remove noise. Gaussian filter uses a kernel that represents the shape of a gaussian (`bell-shaped') hump. A 3x3 pixel window with sigma 0.05 is used in gaussian filter in this case. Wiener filter is based on a statistical approach. Wiener filter is applied to an image adaptively tailoring itself to the local image variance. Where the variance is large, wiener filter performs little smoothing. Where the variance is small, wiener performs more smoothing. This approach often produces better results than linear filtering. Mean filtering is a simple, intuitive and easy to implement method for smoothing images.

In mean filter each pixel value in an image is replaced with the mean value of its neighbors in the window, including itself.

A 3 x 3 kernel is used in this study to implement mean filter as in (3).

$$C=\frac{1}{K}\cdot\begin{bmatrix}1 & 1 & 1\\ 1 & 1 & 1\\ 1 & 1 & 1\end{bmatrix};\ k = \qquad (3)$$

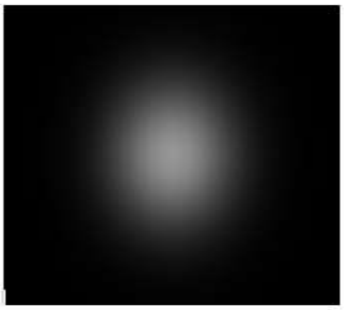

Figure 4. Synthetic gaussian image

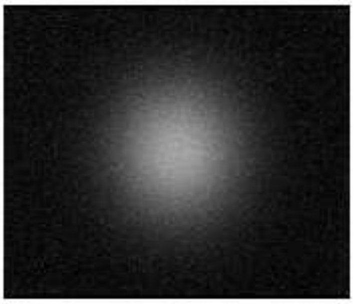

Figure 5. Synthetic gaussian image with added dark frame noise

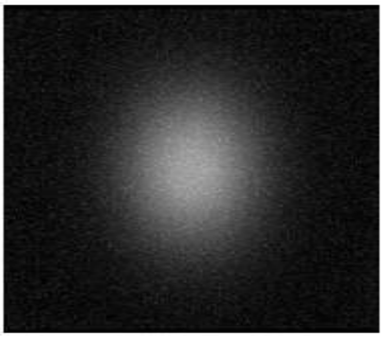

Figure 6. Effect of gaussian filter on noisy image

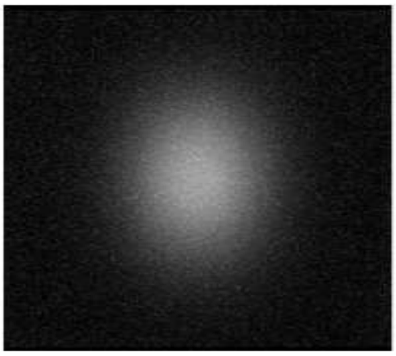

Figure 7. Effect of wiener filter on noisy image

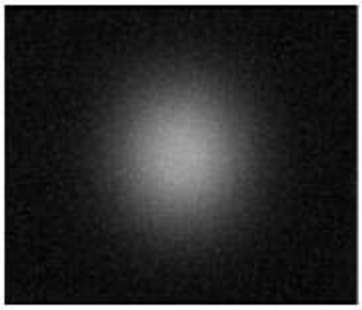

Figure 8. Effect of mean filter on noisy image

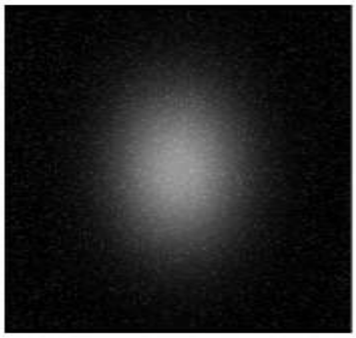

Figure 9. Effect of median filter on noisy image

Fig. 6 shows the effect of gaussian filter on noisy image. Effect of wiener filter on noisy image is shown in fig. 7. Fig. 8 and 9 shows the effect of mean and median filter on noisy image respectively. Table 1 compares the effect of these filters in terms of mean square error (mse) and peak signal to noise ratio (PSNR). The mean square error (mse) is defined as (4)

$$\frac{1}{MN}\sum_{y=1}^{M}\sum_{x=1}^{N}\left[I(x,y) - I'(x,y)\right]^2 \qquad (4)$$

Where I(x, y) is the original image, I'(x, y) is the restored image after applying noise reduction filters. M and N are the dimensions (rows and columns) of the image.

Peak Signal to Noise Ratio (PSNR): It is measured in decibel (dB) and for 8 bit gray scale image it is defined as (5)

$$PSNR = 10 * \log_{10} * 255^2 / mse \qquad (5)$$

As can be seen from table I, noise reduction performance of median filter is best in all the images followed by mean, wiener and gaussian filter. The PSNR ratio of restored image using median filter is also high in comparison with mean, wiener and gaussian filters. Table 2 shows the effect of gaussian, wiener, mean and median filters on beam centroid. It can be observed that filters used in this study do not create any appreciable error in beam centroid measurement. One of the main problem with noise removal filter from digital images is that application of filters may modify the fine details present in the image which is undesirable since it may affect the measurement accuracy of parameters of interest. Noise filtering should be such that it will have minimal effect on beam parameters like beam size and beam centroid. Horizontal (σx) and vertical beam sizes (σy) of the restored image were compared with original image to quantify the effect of gaussian, wiener, mean and median filters on synthetic gaussian image. Ten different dark frame images were used in this study. These dark frame images were collected under identical condition with a short span of time about half an hour.

Each of these background images were added to the synthetic gaussian image. The beam sizes were computed by taking horizontal and vertical line profile data at the beam centroid position in each case. A gaussian function given in (6) was fitted on horizontal and vertical line profile data to compute beam size.

F(x) = a1*exp (-((x-b1)/c1) ^2) (6)

Where a1 is constant, b1 is mean and c1 is sigma of gaussian distribution. Curve Fitting Toolbox available in Matlab 7.9.0 is used to fit the gaussian function on line profile data. Two sigma of gaussian function is defined as beam size in this case. Fig. 10 shows the gaussian fit on a horizontal line profile data after median fit applied on a noisy image at centroid position of the image.

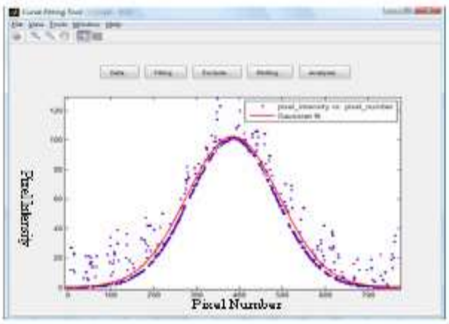

Figure 10. Gaussian fit on horizontal line profile data after median filter

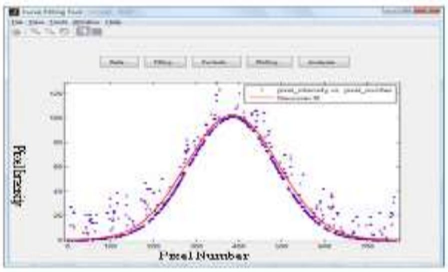

Figure 11. Gaussian fit on vertical line profile data after median filter

Fig. 11 shows the gaussian fit on a vertical line profile data on same image at centroid position. Table III shows the effect of these filters on beam size. From table III, it is possible to say that that the median filter creates less distortion in beam size in comparison with wiener, mean and gaussian filter. Percentage error is defined as

Error % = (filtered image beam size – synthetic image beam size)*100/ synthetic image beam size

Conclusion

Beam size and beam centroid are important parameters in electron accelerators which define the characteristics of beam. Measurement accuracy of these parameters using digital image processing limited by noise level and nature of noise present in images. We have observed that performance of median filter is comparatively better in terms of noise removal efficiency and detail preservation than gaussian, wiener and mean filter on the images collected from Transport Line 1 at Indus Accelerator Complex at RRCAT, Indore, India.

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Table I

Performance of noise removal filters on a synthetic gaussian image corrupted with noise

Image No.	Noisy image		Gaussian filter		Wiener filter		Mean filter		Median filter	
	MSE	PSNR (dB)	MSE	PSNR (dB)	MSE	PSNR (dB)	MSE	PSNR (dB)	MSE	PSNR (dB)
1	602.54	20.33	380.69	22.32	316.02	23.13	244.13	24.25	113.48	27.58
2	620.36	20.02	390.46	22.21	324.67	23.01	249.02	24.17	113.92	27.56
3	603.36	20.32	379.89	22.28	315.18	23.14	242.35	24.28	110.89	27.68
4	590.62	20.41	371.38	22.43	308.30	23.24	237.61	24.37	108.18	27.79
5	600.96	20.342	379.97	22.33	314.63	23.15	244.77	24.24	114.91	27.34
6	626.73	20.16	394.5	22.17	328.95	22.96	252.2	24.11	115.85	27.49
7	657.97	19.95	415.08	21.95	349.48	22.70	265.3	23.89	120.37	27.33
8	616.36	20.23	389.35	22.22	323.01	23.04	250.26	24.15	116.19	27.28
9	620.25	20.20	394.27	22.17	325.92	23.00	255.7	24.05	123.35	27.22
10	602.28	20.33	379.63	22.34	314.68	23.15	242.67	24.28	111.78	27.65

Table II
Effect of Noise Removal Filters on Beam Centroid

Image Number	Synthetic gaussian image		Noisy image		Gaussian filter		Wiener filter		Mean filter		Median filter	
	Centroid (Pixels)		Centroid (Pixels)		Centroid (Pixels)		Centroid (Pixels)		Centroid (Pixels)		Centroid (Pixels)	
1	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
2	385	295	382.6	293.6	382.6	293.6	382.6	293.5	382.6	293.8	382.9	293.5
3	385	295	383	293.9	383	299.9	383	293.4	383	294	383.4	294.7
4	385	295	383.1	293.7	383.1	293.7	383.1	293.7	383.4	293.7	383.5	293.9
5	385	295	383	294	383	294.9	382.9	294.9	382.4	294.8	383.4	295.1
6	385	295	382.9	293.9	382.9	293.9	382.8	294	382.9	293.9	383.9	293.9
7	385	295	383.1	293.1	383.1	293.1	383.1	293	383.1	293.1	383.5	294
8	385	295	383	291.4	383	291.4	382.9	291.4	382.9	291.4	383.3	292.6
9	385	295	382.9	293.7	382.9	293.7	382.9	293.7	382.9	293.7	383.4	294.3
10	385	295	382.9	295.1	382.9	295.1	382.9	295.1	382.9	295.1	383.1	295.1
Mean	385	295	383.2	294.4	383.2	294.4	383.2	294.4	383.2	294.4	383.5	294.7

Table III
Effect of noise removal filters on beam size

Image	Synthetic gaussian image		Noisy image		Gaussian filter		Wiener filter		Mean Filter		Median filter	
Horizontal (σx) and vertical (σy) beam sizes (pixels)												
	σx	σy	σx	σy	σx	σy	σx	σy	σx	σy	σx	σy
1	141.4	141.4	174.7	168.8	175.4	168.2	176.2	167.8	177.2	167.8	155.1	150.5
2	141.4	141.4	175.9	172.6	176.2	170.9	177.7	170.7	176.9	167.5	154.7	150.6
3	141.4	141.4	169.3	172.2	170.1	172.2	173.0	170.8	173.0	167.1	151.8	150.8
4	141.4	141.4	172.9	167.8	173.7	167.8	175.6	168.1	175.3	167.8	153.0	152.8
5	141.4	141.4	173.9	166.5	174.1	166.8	174.3	168.1	174.5	167.4	152.8	153.3
6	141.4	141.4	172.6	167.4	172.6	167.7	174.4	168.2	172.9	168.6	152.3	153.6
7	141.4	141.4	179.4	169.2	179.8	169.0	179.3	167.5	180.5	168.2	158.0	151.0
8	141.4	141.4	174.6	167.9	176.3	167.4	178.4	167.2	179.5	166.3	155.9	149.8
9	141.4	141.4	170.8	167.0	170.8	166.4	172.3	167.3	173.5	165.0	153.2	150.3
10	141.4	141.4	170.9	170.5	171.9	169.8	172.3	169.1	174.2	168.1	155.2	152.2
Mean	141.4	141.4	173.5	168.9	174.1	168.2	175.3	168.4	175.7	167.4	154.2	151.5
Error in %					23 %	18%	24%	19%	24%	18%	9%	7%