Performance Comparison of Various Image Denoising Filters Under Spatial Domain

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ABSTRACT
Image denoising is very important during enhancement of image. Original Image is generally corrupted with various types of noise. The noise present in the images may appear as additive or multiplicative components. The most challenging problem is removing that noise from an Image while preserving its details. Several noise removal techniques have been developed so far each having its own advantages and disadvantages. The focus of this paper is to study various spatial filters and to compare their performance in removing different types of noise. Here quantitative measure of comparison is provided by the Peak Signal to Noise Ratio (PSNR) parameter.

General Terms
Image Denoising, Spatial filtering.

Keywords
Image denoising, Additive or Multiplicative Noise, Peak Signal to Noise Ratio.

1. INTRODUCTION
Digital images play an crucial role in different areas like television, remote sensing, ultrasound, CT scan etc. They are also used in various research areas like Uranology. Images captured by different devices generally adds the different types of noise in them while capturing due to faulty instruments or wrong methods of data capturing. Sometimes noise is added to an image during its transmission over various media . So, denoising the image is an essential task and it is generally done before considering the image for various purpose. An Ideal denoising technique should be able to remove most of noise from image while preserving its fine details [17].

Image denoising is considered as an important step and is generally done prior to processing of an image. It shows the process of recovering a good estimate of the original image from a corrupted image without modifying the useful structure in the image such as edges, discountinuities and fine details [9]. Generally speaking, denoising is the process of removing the unwanted noise from the corrupted image and reconstructing the original image. The main challenge is to design such noise removing techniques which should be able to remove most of noise from noisy image with minimum or no loss of its significant details [13]. It has many applications in other domains like object recognition, digital entertainment, and remote sensing imaging etc. As the number of image sensors per unit area increases, camera devices capture the noise with the image more often. Denoising techniques have become a vital step for improving the visual quality of images which are degarded by different types of noise [2] [6] [7].

Noise can be categorized as Gaussian noise, Uniform noise, Impulse noise (salt and pepper noise)[14] [12] Erlang noise /Gamma noise, Rayleigh noise and Speckle noise each having its own probability density function.

This paper is organized as follows. In section 2 noise model for different types of noise are defined. Section 3 gives the various Spatial image denoising techniques. Section 4 gives the implementation of various filters on images corrupted with different types of noise. Finally, Section 5 gives the conclusion and Section 6 gives the Furture scope of the work. At the end, Appendix is given which consists of 4 Tables and 4 Figures which shows the performance of various Spatial filters.

2. NOISE MODELS
Noise is generally added to image during image capturing or due to faulty image capturing hardware. For e.g. during acquiring images with CCD camera, the two major factors which affect the amount of noise in the image are sensor temperature and light levels. Images are also corrupted during transmission due to interference in the channel [11].

The degradation process is shown below. Here degradation function and additive noise, both are added to the original input image f(x,y) to produce a degraded image g(x,y). Given g(x,y), some idea about the degradation function H and additive noise term n(x.y), one can acheive the estimate f^(x.y), of the original input image by using the restoration model. In general, the more one has idea about H and n(x,y), the closer estimate to f(x,y) one will obtain. The degradation model can be represented with the following equation.

$$g(x,y) = h(x,y) \times f(x,y) + n(x,y) \tag{1}$$

Here f(x,y) is the original image pixel value and n(x,y) is the additive noise, h(x,y) be the degradation function and g(x ,y) is the resulting noise image. [19]

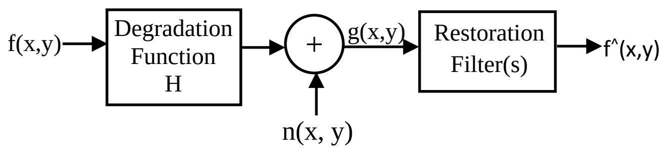

Fig. 1 A model of the image degradation/restoration process [19]

The Different types of Noise models are described below :

2.1 Gaussian Noise or Amplifier Noise
It is also known as Gaussian distribution. It has a probability density function (PDF) of the normal distribution. This noise is added to image during image acquisition like sensor noise caused by low light, high temperature, transmission e.g. electronic circuit noise [7]. This noise can be removed by using spatial filtering (mean filtering, median filtering and gaussian smoothing) by smoothing the image but smoothing also blurs the fine-scaled image edges and details. [4]. The PDF of Gaussian Noise is shown in the following equation and figure :

$$p(z) = \frac{1}{\sqrt{2\pi\sigma}} e^{-(z-\mu)^2/2\sigma^2} \quad (2)$$

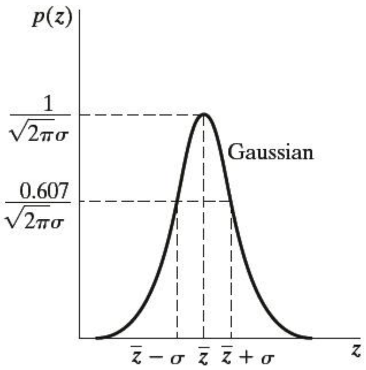

Fig. 2 PDF of Gaussian Noise


Fig. 3 Image containing Gaussian Noise

2.2 Impulse Noise

The Impulse noise is also known as Salt & Pepper noise or Spike noise. It is caused by malfunctioning pixels in camera sensors, faulty memory locations in hardware, or transmission in a noisy channel [1]. It is always Independent and uncorrelated to image pixels. Its two types are the salt-and-pepper noise and the random-valued noise. In salt and pepper type of noise, the noisy pixels takes either salt value (gray level -225) or pepper value (grey level -0) and it appears as black and white spots on the images In case of random valued impulse noise, noise can take any gray level value from zero to 225. In this case also noise is randomly distributed over the entire image and probability of occurrence of any gray level value as noise will be same [5].

Reasons for Salt and Pepper Noise*:*

1) Due to failure of memory cells or wrong working of sensor cells of camera.
2) Due to synchronization errors while transmitting image over media [18].

The PDF of Impulse noise is shown in following equation and figure :

$$\text{p(z)} = \begin{cases} p_a & for\ z = a \\ p_b & for\ z = b \\ 0 & otherwise \end{cases} \quad (3)$$

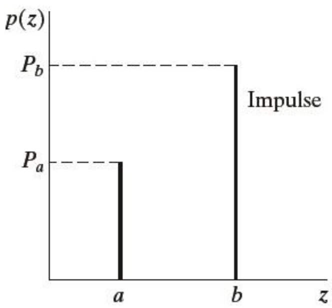

Fig. 4 PDF of Impulse (Salt & pepper) Noise


Fig. 5 Image containing Impulse Noise

2.3 Speckle Noise

Speckle noise is a granular noise. This noise generally degrades Synthetic Aperture Radar (SAR) images to large extent. This noise is generally caused due to random ups and downs in the signal coming back from an object that is smaller than a single image-processing element. It is also caused by consistent processing of backscattered signals from a no of distributed targets. This noise also increases the mean grey level of affecting image. This noise creates a lot of difficulty in interpreting the image. [20].


Fig. 6 Image Containing Speckle Noise

2.4 Poisson Noise

Poisson noise is also known as Photon noise. It arises when number of photons sensed by the sensor is not sufficient to provide detectable statistical information [16]. This noise has root mean square value proportional to square root intensity of the image. Different pixels are suffered by independent noise values. The photon noise and other sensor based noise corrupt the signal at different proportions [15]. The PDF of Poisson Noise is shown in following equation and figure :

$$p(x) = \frac{e^{-\lambda}\lambda^x}{x!}\ for\ \lambda > 0 \text{ and } x=0,1,2\ ... \quad (4)$$

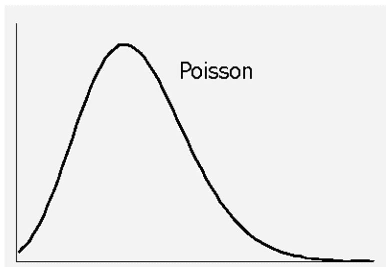

Fig. 7 PDF of Poisson Noise

Fig. 8 Image containing Poisson Noise

2.5 Uniform Noise

The Uniform noise caused by quantizing the pixels of image to a number of distinct levels is known as Quantization noise. It has approximately uniform distribution. In this type of noise, the level of the gray values of the noise are uniformly distributed over a specified range. It can be used to create any type of noise distribution. This type of noise is mostly used to evaluate the performance of image restoration algorithms. This noise provides the most neutral or unbiased noise [10]. The PDF, mean and variance of Uniform Noise is shown below:

$$p(z) = \begin{cases} \frac{1}{(b-a)}, & if\ a \le z \le b \\ 0, & otherwise \end{cases} \quad (5)$$

$$\mu = (a+b)/2 \quad (6)$$

$$\sigma^2 = (b-a)^2/12 \quad (7)$$

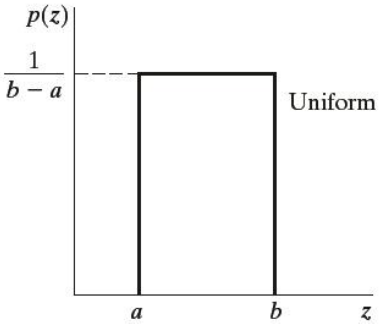

Fig. 9 PDF of uniform noise

Fig. 10 Uniform Noise present in an Image

2.6 Rayleigh Noise

Radar range and velocity images typically contain noise that can be modelled by the Rayleigh distribution [18]. The PDF, mean and variance of Rayleigh Noise is given below:

$$p(z) = \begin{cases} \frac{2}{b}(z-a)e^{\frac{-(z-a)^2}{b}} & for\ z \ge a \\ 0 & for\ z < a \end{cases} \quad (8)$$

$$\mu = a + \sqrt{\pi b/4} \quad (9)$$

$$\sigma^2 = \frac{b(4-\mu)}{4} \quad (10)$$

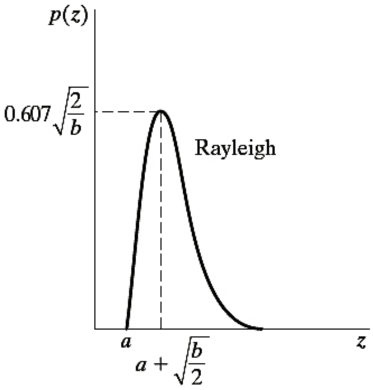

Fig. 11 PDF of Rayleigh Noise

Fig. 12 Image containing Rayleigh Noise

2.7 Gamma Noise

This type of noise can be obtained by the low-pass filtering of laser based images [18]. The PDF, mean and variance of Gamma Noise is given below:

$$f(x) = \begin{cases} \frac{a^z z^{b-1}}{(b-1)!} e^{-az}, & for\ z < 0 \\ 0, & for\ z \ge 0 \end{cases} \quad (11)$$

$$\mu = b/a \quad (12)$$

$$\sigma^2 = b/a^2 \quad (13)$$

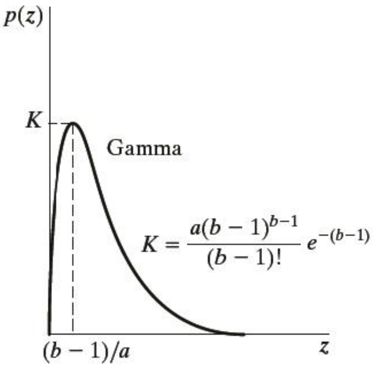

Fig. 13 PDF of Gamma noise

Fig. 14 Image containing Gamma Noise

3. IMAGE DENOISING TECHNIQUES

There are different Image denoising techniques developed so far each having its own advantages and limitation. One should choose the techniue accoring to the type and amount of noise present in the image. One should also consider the other factors like performance in denoising the image, computational time, computational cost.

Denoising can be done in various domains like Spatial Domain, Frequency Domain and Wavelet Domain. The Spatial domain method is discussed below.

3.1 Spatial Domain

Here filtering is used for image noise removal. Filtering is a technique in image processing which is used for different tasks like noise reduction, interpolation, and re-sampling. It is mostly used in all image processing systems. The choice of filter depend upon the type and amount of noise present in an image because different filters can remove different types of noise efficiently.

Spatial Domain has following types of filters :

3.1.1 Linear Filters:

Linear filters are used to remove certain type of noise. Here filtering is generally done by blurring the image. These filters blur the edges and destroy the fine details of an image. They have poor performance in removing signal dependent noise. Gaussian and Averaging filters are commonly used linear filters [8]. They are of following types :

3.1.1.1 Gaussian Filter:

Gaussian filter is a non-uniform low pass filter. Gaussian filter is used to blur images and remove noise and detail. It does not remove salt & pepper noise effectively [3].

3.1.1.2 Average Filter:

The output of average filter is simply the average of pixels contained in the neighborhood of filter mask. It calculates the average of all intensities of the neighbourhood of the central pixel and repacles the pixel with that average value . It is mostly used in removing irrelevant details from an image. It has a limitation that it blurs the edges of the image [19].

3.1.2 Non-Linear Filters:

In recent years, a variety of non-linear filters such as median filter, min filter, max filter have been developed to overcome the shortcoming of linear filter. Non-linear filters exhibit better performance than linear filters [10]. They are discussed below :

3.1.2.1 Mean Filter:

It is one of the most simplest filter among the existing spatial filters. It uses a filter window which is usually square. The filter window replaces the center value in the window with the average mean of all the pixels values in the kernel or window.

3.1.2.2 Median Filter:

It is also known as order statistics filter. It is most popular and commonly used non linear filter. It removes noise by smoothing the images. This filter also lowers the intensity variation between one and other pixels of an image. In this filter, the pixel value of image is replaced with the median value The median value is calculated by first arranging all the pixel values in ascending order and then replace the pixel being calcuated with the middle pixel value. If the neighbouring pixel of image which is to be consider, contains and even no of pixels, then it replaces the pixel with average of two middle pixel values. The median filter gives best result when the impulse noise percentage is less than 0.1 It does not perform well in removing high density salt & pepper noise [19]. The mean filter can be represented by the following equation :

$$f^\wedge(x,y) = median\{g(s,t)\}\ where\ (s,t) \in S_{xy} \tag{14}$$

Here S_{xy} corresponds to the set of coordinates in a rectangular subimage window which has center at (x,y). The median filter calculates the median of the corrupted image g(x,y) under the area $S_{xy.}$ Here f^(x,y) represents the restored image.

3.1.2.3 Min Filter:

Min filter is also known as 0^{th} percentile filter. It replaces the value of pixel by the minimum intensity level of the neighborhood of that pixel.. This filter finds darkest points in an image. It removes salt noise from an image containing salt and pepper noise due to its high intensity value [19]. The min filter can be represented by the following equation :

$$f^\wedge(x,y) = min\{g(s,t)\}\ where\ (s,t) \in S_{xy} \tag{15}$$

3.1.2.4 Max Filter:

Max filter is also known as 100^{th} percentile filter. It replaces the value of pixel by the maximum intensity level of the neighborhood of that pixel. This filter finds brightest points in an image. It removes pepper noise from an image containing salt and pepper noise due to its very low intensity value [19].

$$f^\wedge(x,y) = max\{g(s,t)\}\ where\ (s,t) \in S_{xy} \tag{16}$$

3.1.3 Adaptive Filters :

These filters works accordingly the statistical characteristics of image inside inside the filter region defined by the mxn rectangular window. They are more complex and gives better performance than existing spatial filters. The most commonly used spatial filter is adaptive median filter which is discussed below :

3.1.3.1 Adaptive Median Filter :

It performs well on images containing high density salt & pepper noise. It preserves the details of an image while smoothing non impulse noise. It changes its windows size during its operation depending on the certain conditions [19]. It works in two stages. First it calculates the minimum , maximum and median values of subimage window of the corrupted image. In stage one , it checks whether the calculated median itself is a salt or pepper noise or not. If the median is salt or pepper noise, then it increase the size of subimage window and recalculates the mimum, maximum and median values otherwise it proceeds to stage two. In stage two, it checks whether the selected pixel is a salt or pepper noise or not. If it is salt or pepper noise, then it replaces the selected pixel with previously calculated median otherwise the pixel remains unchanged.

4. IMPLEMENTATION AND RESULTS

Experiments were carried out on various standard grayscale images of size 256 x 256 which are of jpeg format and are shown in Figure 18. Simulation is performed using matlab R2013a software.

Fig. 15 Original Images used for simulation (a) Lena, (b) Barbara, (c) Boat, (d) Baboon

The input images are corrupted by a simulated Gaussian white noise (mean=0, variance=0.01), Salt & Pepper noise (noise density= 0.05), Speckle noise (mean=0, variance=0.04), Poisson noise, Uniform noise (interval [0,1]), Rayleigh noise (parameters 0,1), Erlang noise (parameters 2,5). For denoising process, various spatial linear filters which are gaussian filter (3x3), average filter (3x3) and spatial nonlinear filters which are median filter (3x3), min filter (3x3), max filter (3x3) and adaptive filters which are adaptive median filter (3x3), have been used.

The Quantitative performance of the spatial filters is evaluated through Peak signal to noise ratio (PSNR). It can be defined by following eq.

$$PSNR = 10\log_{10}\left(\frac{255^2}{MSE}\right) \quad (17)$$

$$MSE = \frac{\sum_i \sum_j (r_{ij} - x_{ij})}{M \times N} \quad (18)$$

Where *r* refers to Original image, *x* denotes the restored image, M x N is the size of processed image.

Table 1 in the Appendix A shows performance of various spatial filters in removing the different types of noise in Lena image, in terms of psnr. Similarly Tables 2, 3 and 4 corresponds to Barbara, Boat and Baboon image respectively. Figure 16 shows the lena image corroupted with different noise types and each noisy image filtered using different filters. Similarly Figure 17, 18 and 19 corresponds to Barbara, Boat and Baboon image respectively.

5. CONCLUSION

In this paper, various noise models and filtering techniques like linear, nonlinear filtering and adaptive filtering have been discussed. The seven different types of noises which includes Gaussian noise, Salt & Pepper noise, Speckle noise, Poisson noise, Uniform noise, Rayleigh noise and Erlang noise, were simulated on four different standard test images. Then six different spatial filters which includes Average filter, Gaussian filter, Min filter, Max filter, Median filter & Adaptive Median filter, were applied on different noisy images.. The performance of the filters was evaluated using PSNR parameter. The comparison results show that Average filter shows better performance in removing Gaussian and Speckle noise while Gaussian filter removes Poisson noise efficiently. The adaptive median filters performed well in removing Salt & Pepper , Uniform, Rayleigh and Erlang noise.

6. FUTURE SCOPE

This comparative study can be further extended by including more noise types like Exponential noise, Anisotropic noise, Film grain etc and/or by using multiple types of noise in different types of images. One can include more spatial filters using various means filters like Arithmetic mean filter, Geometric mean filter, Harmonic mean filter, Contraharmonic mean filter and order statistics filters like Midpoint filter, Alpha trimmed filter and Adative filters like Adaptive local noise reduction filter for comparison. One can also use hybrid filtering approach which involves two or more filters. Some other parameters like Entropy, Structure Similarity Index and Image Quality can also be considered for measuring the performance of different filters.

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Appendix A

Table 1. Peformance comparison of various filters on different types of noise using lena image

Type of Noise	Denoised Image PSNR					
	Linear Filters		Non Linear Filters			Adaptive Filters
	Gaussian Filter	Average Filter	Median Filter	Min Filter	Max Filter	Adaptive Median Filter
Gaussian noise	23.7253	25.8026	25.4979	14.7697	14.6815	22.7467
Salt & Pepper noise	22.1794	24.9387	30.5088	12.1861	11.7244	37.4839
Speckle noise	22.5712	25.1905	23.3750	14.7026	14.2945	20.7189
Poisson noise	30.0853	27.5862	29.2124	18.8530	18.4931	28.7065
Uniform noise	23.7290	25.4830	30.6693	20.8097	10.9641	34.6640
Rayleigh noise	17.9421	20.7429	27.2467	20.9664	7.0116	29.3020
Erlang noise	25.6125	26.3890	30.9288	20.7841	12.3587	34.9521

Table 2. Performance comparison of various filters on different types of noise using barbara image

Type of Noise	Denoised Image PSNR					
	Linear Filters		Non Linear Filters			Adaptive Filters
	Gaussian Filter	Average Filter	Median Filter	Min Filter	Max Filter	Adaptive Median Filter
Gaussian noise	23.5245	24.7801	24.2943	14.7023	14.4711	22.3013
Salt & Pepper noise	21.9990	24.0744	26.9224	12.7807	11.2108	30.6652
Speckle noise	23.0974	24.6848	23.2255	15.1969	14.3174	21.1005
Poisson noise	29.6819	26.1732	26.3985	18.7506	18.3279	27.3986
Uniform noise	23.0142	24.3241	26.9576	20.4592	10.3217	30.7675
Rayleigh noise	17.3943	20.0719	25.4286	20.6026	6.5150	28.1467
Erlang noise	23.5245	24.7801	24.2943	14.7023	14.4711	22.3013

Table 3. Peformance comparison of various filters on different types of noise using boat image

Type of Noise	Denoised Image PSNR					
	Linear Filters		Non Linear Filters			Adaptive Filters
	Gaussian Filter	Average Filter	Median Filter	Min Filter	Max Filter	Adaptive Median Filter
Gaussian noise	23.7516	26.0948	25.7364	14.8648	14.6925	22.6735
Salt & Pepper noise	25.0062	25.0062	30.9745	11.7478	11.9887	35.7980
Speckle noise	22.0179	25.1206	22.9734	14.3615	13.8254	20.1106
Poisson noise	30.0707	27.9380	29.3486	18.9826	18.7393	28.5874
Uniform noise	24.3334	26.0411	31.2354	21.2726	11.4607	36.0756
Rayleigh noise	18.4553	21.2884	28.1451	21.4167	7.4662	30.6818
Erlang noise	25.8548	26.7381	31.3529	21.2579	12.6767	36.2143

Table 4. Performance comparison of various filters on different types of noise using baboor image

Type of Noise	Denoised Image PSNR					
	Linear Filters		Non Linear Filters			Adaptive Filters
	Gaussian Filter	Average Filter	Median Filter	Min Filter	Max Filter	Adaptive Median Filter
Gaussian noise	23.3947	23.2433	22.8770	13.7440	13.6688	21.7374
Salt & Pepper noise	21.9674	22.7230	24.7019	11.9235	11.2608	28.5596
Speckle noise	22.4662	22.9644	21.8168	14.0948	12.9185	20.2397
Poisson noise	28.9512	24.1477	24.4255	16.7472	16.3791	26.0859
Uniform noise	23.5889	23.1212	24.7775	17.7671	10.7721	28.5887
Rayleigh noise	17.9740	19.8989	23.5495	17.9327	7.0417	26.4316
Erlang noise	25.2397	23.5805	24.8731	17.7486	11.9858	28.6750

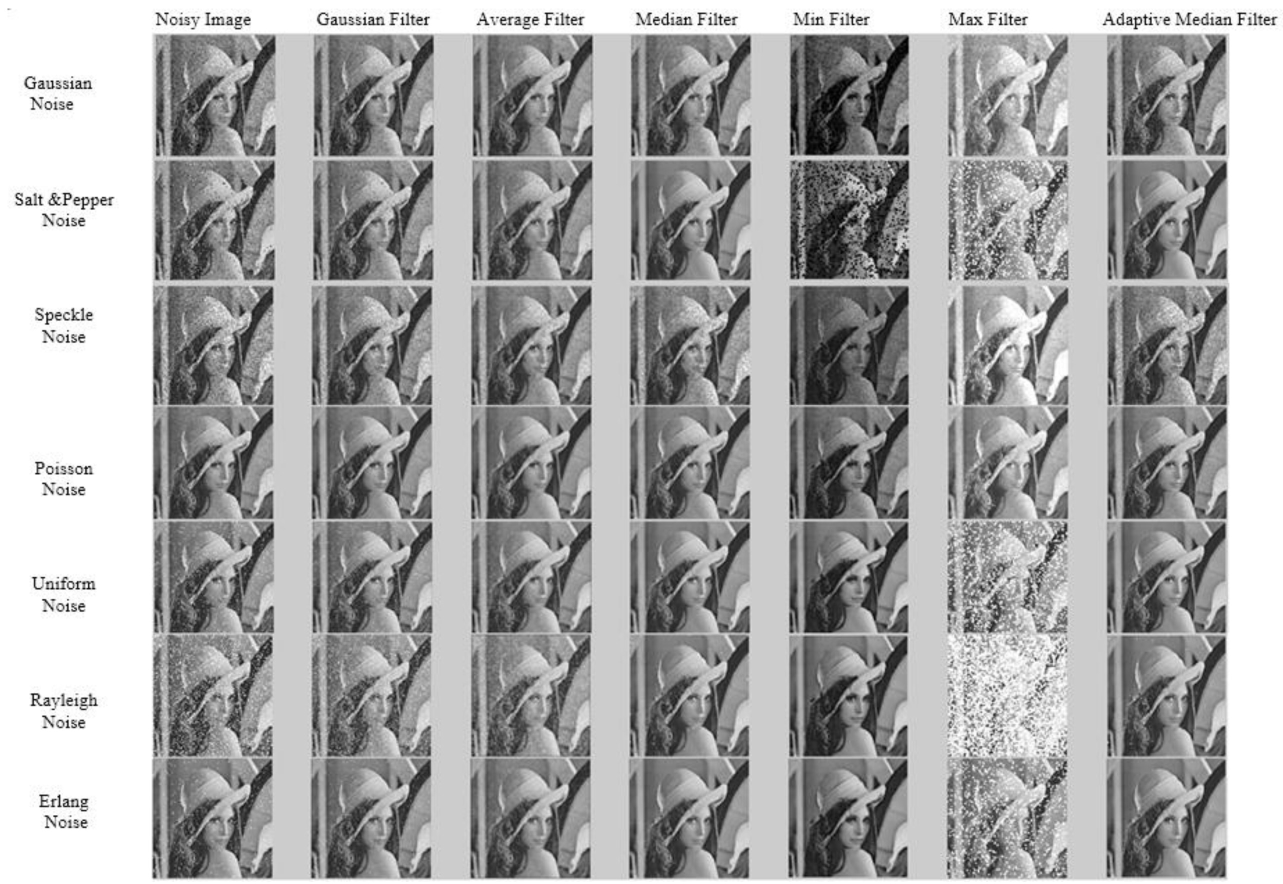

Fig. 16 Lena image containing various types of noise and filtered by using different spatial filters

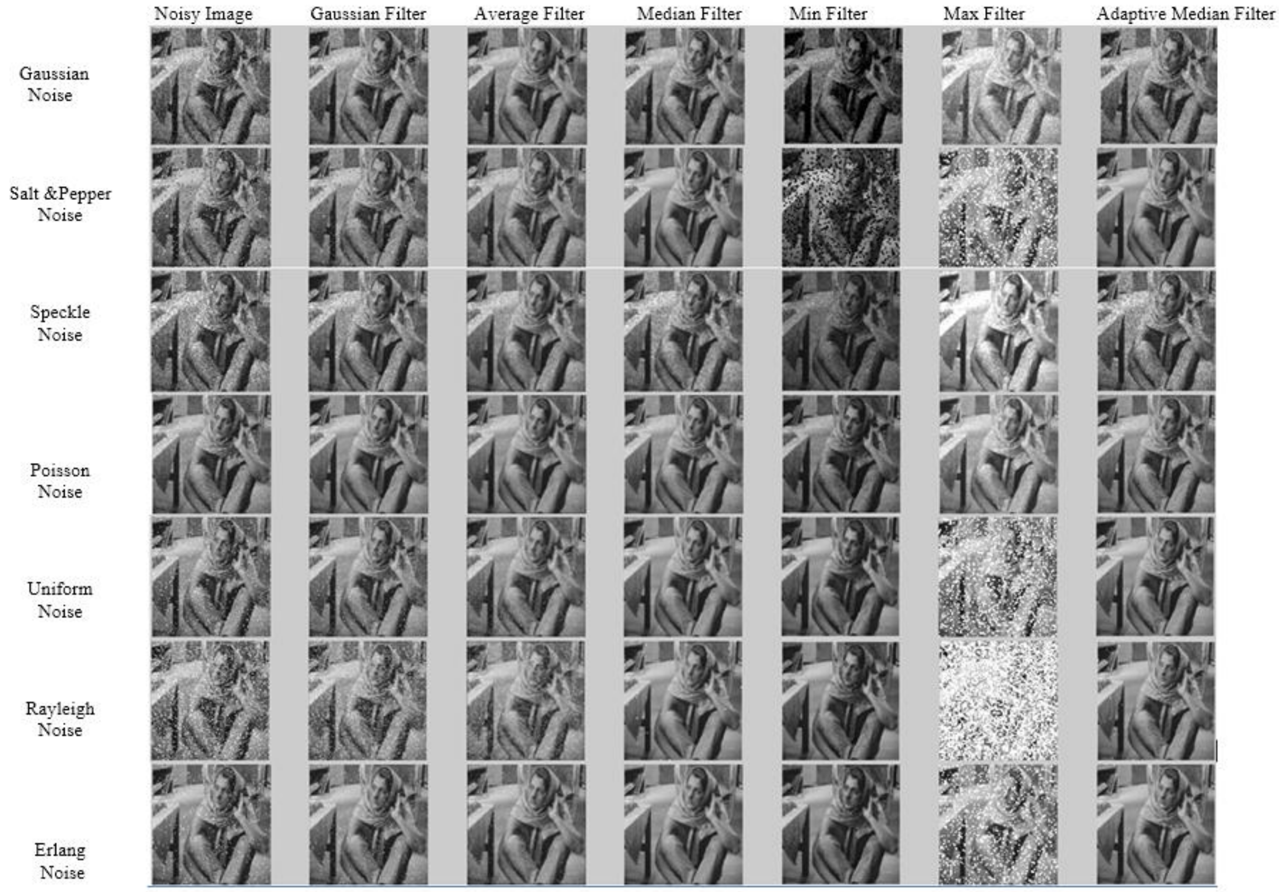

Fig. 17 Barbara image containing various types of noise and filtered by different spatial filters.

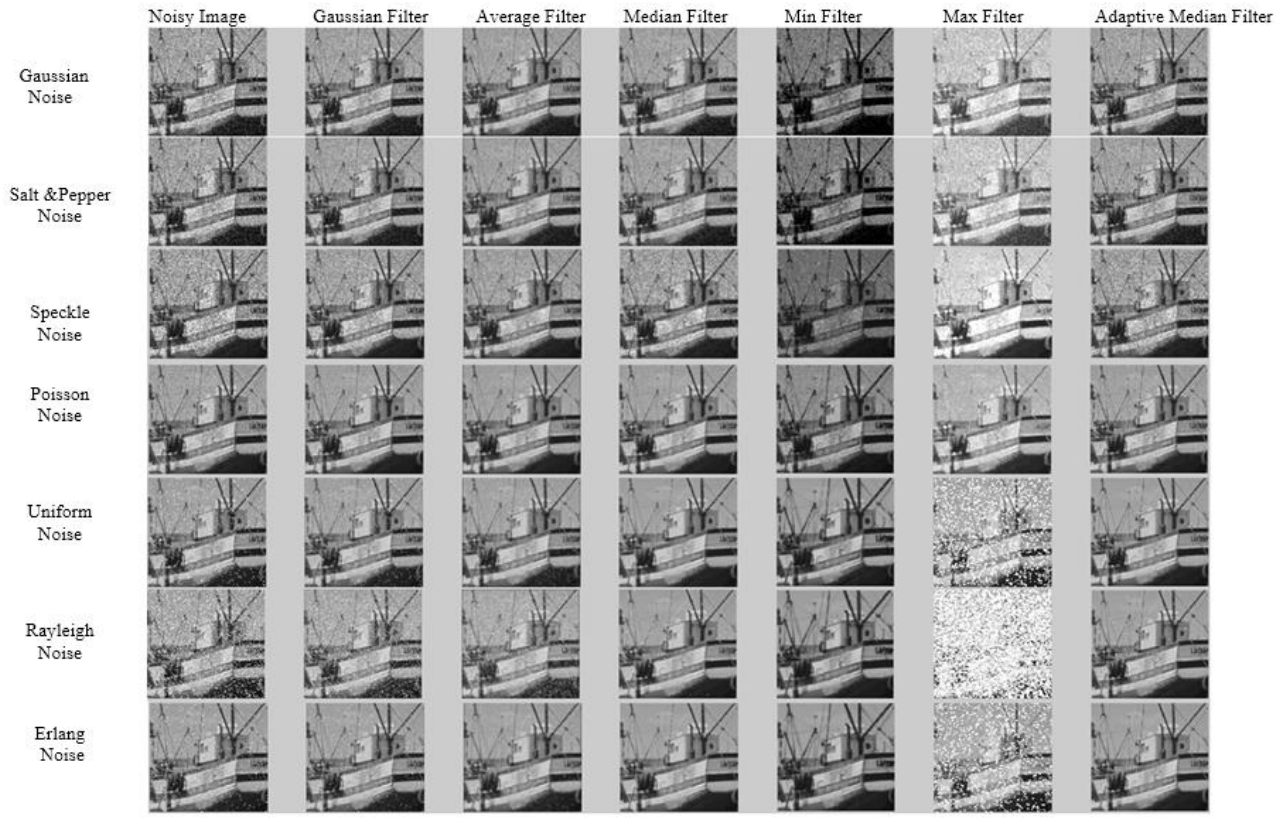

Fig. 18 Boat image containing various types of noise and filtered by different spatial filters

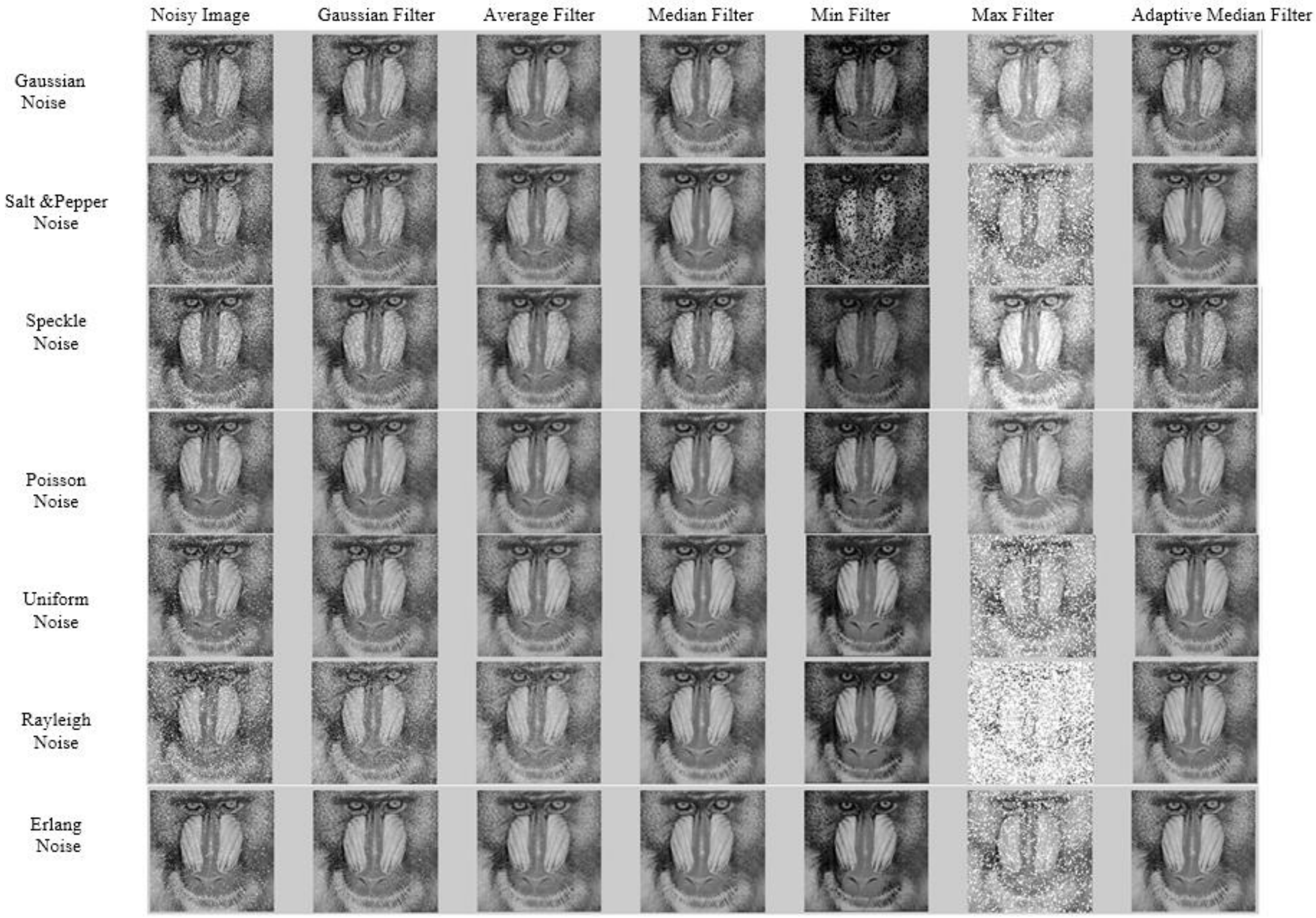

Fig. 19 Baboon image containing various types of noise and filtered by different spatial filters