Edge-Directed Error Diffused Digital Halftoning: A Steerable Filter Approach

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Abstract

In this paper the edge-directed error diffused digital halftoning in noisy media is analyzed. It is known that there occurs error in transmitting data through a communication channel due to addition of noise, generally additive white Gaussian noise (AWGN). The proposed work employs Steerable stochastic error diffusion (SSED) approach, a hybrid scheme that utilizes the advantages of Steerable filter for edge detection purpose and five neighbor stochastic error diffusion (FNSED) approach for error diffusion purpose. Analysis of different methods of edge-detection and error diffusion in the presence of zero mean AWGN with different values of variance has also been made. The results show that the proposed scheme produces halftones of better quality in the presence of even large value of noise variance compared to other approaches of edge detection and error diffusion.

Keywords: *Digital Halftoning, Edge Detection, Stochastic Error Diffusion, AWGN, Steerable Filter, Digital Image Processing*

1. Introduction

Digital halftoning is the process of converting a multi-tone image to a two-tone image. The process of halftoning is possible due to the human eye perception. A halftoned image that gives perception of continuous tone output has only two shades i.e. black & white [1]. The concept of halftoning is used mainly in printing newspapers, magazines, facsimile machines, printers etc.

The methods of obtaining a halftoned output from a continuous tone input can be categorized as classical screening [2], dot diffusion [3], direct binary search [4] and error diffusion [5]. All of these four halftoning methods are used in modern desktop printers.

Classical screening, the oldest method of halftoning in printing works on the principle of applying a periodic array of thresholds to each shade of multi-tone image [2]. Pixels are converted to 0 (black) if they are below threshold otherwise to 1(white). This method suffers from periodic artifacts. Knuth [3] introduced dot diffusion method which works on one design parameter i.e. class matrix C. This method retains the good features of error diffusion [6]. In direct binary search (DBS) method best binary pattern is iteratively searched to produce blue noise halftones in order to match a given grayscale image by minimizing a distortion criterion [2]. In view of complexity in implementation this halftoning method is not used in desktop printers. Error diffusion method that produces halftones of much higher quality is less complex to implement [5]. Hence it is the most popularly used method for halftoning.

Edge, an important part in any image, plays a significant role in our perception of halftoned image. Edge in an image is defined as a set of connected pixels that lie on the boundary between two regions [7]. It represents the areas where an abrupt change in intensity occurs from one pixel to the next. One of the major problems with traditional error diffusion based digital halftoning is that edges in halftoned output are not preserved. Due to diffusion of error across edges in the image, objects are not clearly visible. To overcome this problem, Xin [8] proposed a method to extract a binary edge map from the given image. The edge map information is then used to stop error diffusion at edges to preserve them.

In general additive white Gaussian noise gets introduced in the image transmitted through the channel [9]. Various methods for detecting the edges from a noisy image reported in the literature have not considered digital halftoning concept. In this paper, Steerable stochastic error diffusion (SSED) scheme is proposed which produces better quality halftones in the presence of noise. The following sections of the paper are organized as follows. Section 2 deals with edge detection and error diffusion methods individually. The proposed approach is discussed in section 3. Section 4 presents the results obtained and comparison between various methods used in the work. Finally, conclusion is given in section 5.

2. Edge detection and error diffusion methods for digital halftoning

In this section we first discuss the commonly used methods for detecting the edges from a noisy image in this paper. Next the basic concept of error diffusion and the methods employed for generating high quality halftones are considered.

2(a). Commonly used edge detection methods

2(a).i. Multi scale morphological edge detector

This method detects edges precisely in noisy conditions [10]. Based on two most commonly used morphological operations *dilation* and *erosion*, two compound operations namely *opening* and *closing* are derived [7]. In this operation, basically two images are worked upon: the original image which has to be processed and the structuring element or kernel on the image. In multi scaling approach structuring elements of various sizes are taken to extract edges from image at different scale. In multi scaling operation the small sized structuring element detects fine edges but its performance in terms of noise reduction is not good. On the contrary, the large sized structuring elements perform well in terms of noise reduction at the cost of increased thickness of edges. Therefore, the size of structuring elements is varied appropriately. With varied sized structuring elements, the edge strength maps using the dilation and erosion residue edge detectors are obtained [10]. These edge maps are then combined by applying weighted averaging approach. By thresholding, the final edge map is then obtained.

The edge- maps of noisy images, with structuring elements of sizes 3, 5 and 7, thus generated by this method for two values of variance of noise are shown in figures 1(c) and 2(c).

The drawback of this method is that the edge map obtained is dotted and in the presence of high noise, its performance to detect the edges degrades as visible clearly in figures 1(c) and 2(c).

2(a).ii. Canny edge detector

The Canny method finds edges by looking for local maxima of the gradient of intensity image [11]. The gradient is calculated using the derivative of a Gaussian filter.

In the presence of noise, its performance to detect the edges degrades sharply compared to other methods of edge detection discussed in this paper. As shown in figures 1(d), 2(d) this method provides false edge detections in the edge maps.

2(a).iii. Sobel edge detector

This method finds edges using the Sobel approximation to the derivative of intensity. The points, where the gradient of image intensity has a maximum value are taken as edges of the image [7].

The edge- map obtained with Sobel detector in presence of high noise is better compared to the ones obtained with above two methods. The Steerable filter edge- detection method provides better results.

2(a).iv. Steerable filter edge detector

Steerable filter realizes a filter of arbitrary orientation using a weighted combination of a set of 'basis filters' [12]. These filters are rotation-invariant linear operators that may be used to analyze local orientation patterns in images. In these filters, the response at various orientations is calculated at different angles, taken adaptively.

Consider a two dimensional Gaussian function G

$$G(m,n) = e^{-(m^2+n^2)} \qquad (1)$$

for a pixel location (m, n).

Denoting the ith derivative of Gaussian function in the horizontal direction by G_i , its first derivative in horizontal direction, $G_1^{0^\circ}$ may be expressed as:

$$G_1^{0^\circ} = -2m\, e^{-(m^2+n^2)} \qquad (2)$$

The derivative of same function $G_1^{90^\circ}$ in perpendicular direction may be obtained by applying a rotation of 90°, may be expressed as:

$$G_1^{90^\circ} = -2n\, e^{-(m^2+n^2)} \qquad (3)$$

Based on equations (2) and (3) the filter function G_1^{ψ} at any arbitrary angle ψ may be represented as a weighted combination of $G_1^{0^\circ}$ and $G_1^{90^\circ}$

$$G_1^{\psi} = \cos(\psi)\ G_1^{0^\circ} + \sin(\psi)\ G_1^{90^\circ} \qquad (4)$$

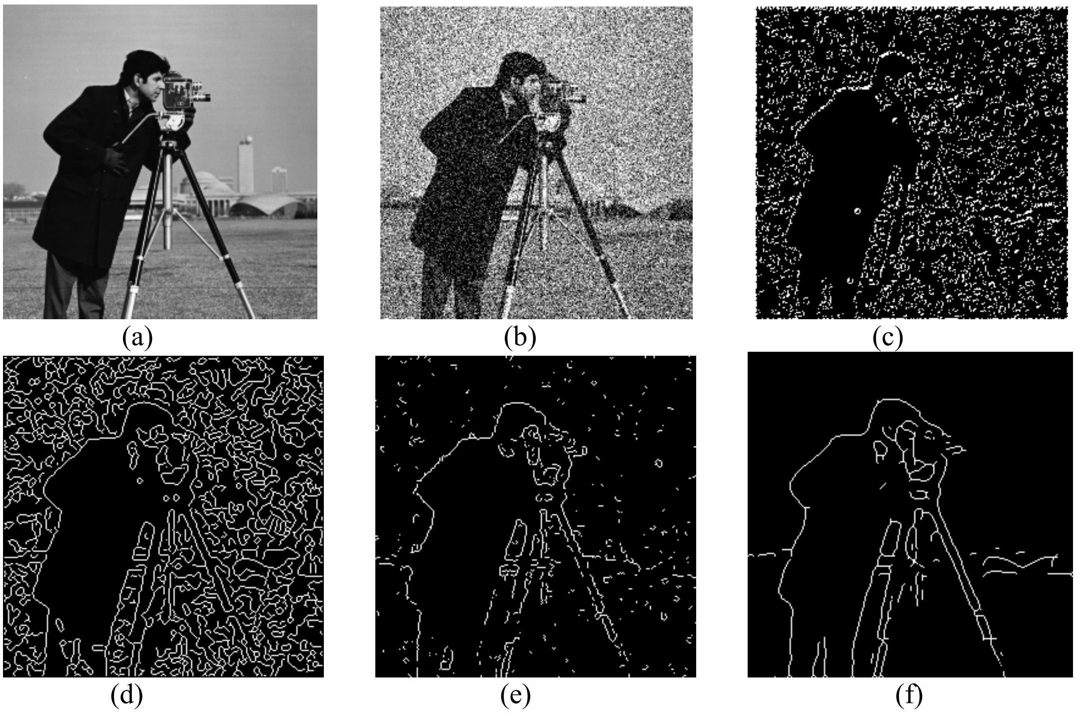


Figure 1. Edge maps obtained by different edge- detectors in presence of Gaussian noise of 0.05 variance (a) input cameraman image (b) noisy image with 0.05 variance (c) multiscalemorphological edge detector (d) Canny edge detector (e) Sobel edge detector (f) Steerable filter edge detector

where $G_1^{0^\circ}$ and $G_1^{90^\circ}$ are the basis filters for G_1^{ψ}, and cos(ψ) & sin(ψ) are the interpolation functions for these basis filters respectively.

For the purpose of edge detection as defined in [12] the orientation energy using Hilbert transform and Gaussian transform of bandpass filter of angle ψ is measured. For all the points (pixels) in the image, a given point (m_o, n_o) is a contour point if orientation energy is at a local maximum in the direction perpendicular to the local orientation.

For noisy input image this filter takes the derivative of an arbitrary isotropic window function (say f(m,n)) in increasing orders to compute the edge point [13] described by h(m,n) as follows:

$$h(m,n) = \sum_{k=1}^{M} \sum_{i=0}^{k} \alpha_{k,i} \frac{\partial^{k-i}}{\partial m^{k-i}} \frac{\partial^{i}}{\partial n^{i}} f(m,n) \qquad (5)$$

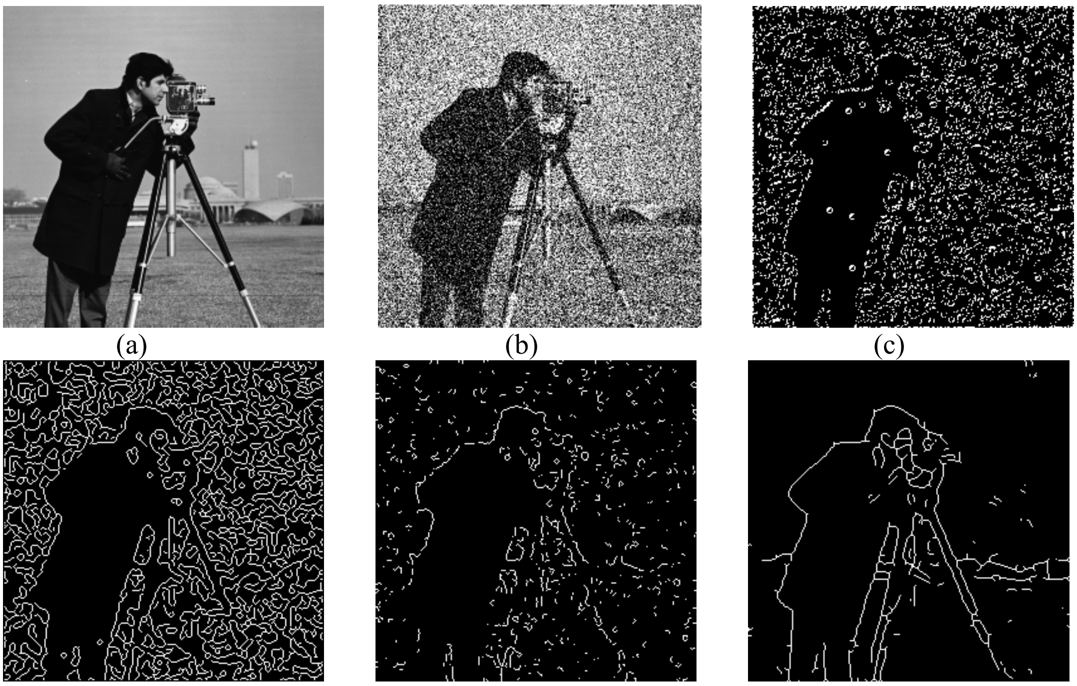
where M denotes the order of filter function h(m,n).

The performance of fifth order derivative of Gaussian is better compared to lower order derivatives in the sense that there are very little false detections and edge detection is very precise [13]. The expression of fifth order derivative obtained in [13] may be expressed as:

$$-1.1215\, f_n - 0.5576\, \sigma^2 f_{mmn} - 0.018\, \sigma^2 f_{nnn} - 0.0415\, \sigma^4 f_{mmmmn} - 0.0038\, \sigma^4 f_{mmnnn} \quad (6)$$

Therefore fifth order derivative steerable filter has been used to extract the edge map.

The results of edge maps in the presence of various values of variance of noise obtained by this method are shown in figures 1(f) and 2(f). These results clearly show that the edge maps obtained by this method especially with the noise of variance having 0.1 value are much better than other three methods discussed.



(a) (b) (c)
(d) (e) (f)

Figure 2. Edge maps obtained by different edge- detectors in presence of Gaussian noise of 0.1 variance (a) input cameraman image (b) noisy image with 0.1 variance (c) multiscalemorphological edge detector (d) Canny edge detector (e) Sobel edge detector (f) Steerable filter edge detector

2(b). Error diffusion technique and employed methods

Error diffusion is one of the best methods for generating high quality halftone. In this method, to get halftoned output, the given input image I (m, n) (which may be color or gray-scale) is first compared with a threshold value. This process gives another image B (m, n) (binary image) which will have reduced gray levels as expected because of thresholding operation. If the highest intensity value is L, then generally L/2 (fixed thresholding) is chosen as the threshold value. For each and every pixel in the image, its gray value is compared with this threshold value. This comparison results in a white pixel if pixel's gray value is greater than the threshold otherwise it results in a black pixel. This process results in quantization error $Q_e(m, n)$ which is calculated as

$$Q_e(m, n) = B(m, n) - I(m, n) \qquad (7)$$

For a current pixel under processing, this quantization error $Q_e(m,n)$ along with some error diffusion weight, is then diffused to its immediate neighboring pixels which are still unprocessed and this alters their previous values. For neighboring pixel with location (x, y), this process of error diffusion is given by the following equation

$$I(m, n) = I(m, n) + W_{x-m,\, y-n}\, Q_e(m, n) \qquad (8)$$

where $W_{x-m,\, y-n}$ represents the error diffusion weight. Depending upon the weight factor (fixed or stochastic weight μ) and the number of neighboring pixels to whom the above computed error be diffused, the following methods of error diffusion are used.

2(b).i. Floyd-Steinberg error diffusion

As proposed by Floyd and Steinberg [5], the following fixed weights are diffused to four neighboring pixels as shown in figure 3.

	*	7/16
3/16	5/16	1/16

Figure 3. Floyd- Steinberg's error diffusion weights

where * denotes the current pixel being processed. The block diagram in figure 4 clearly depicts the whole process of Floyd- Steinberg's error diffusion algorithm.

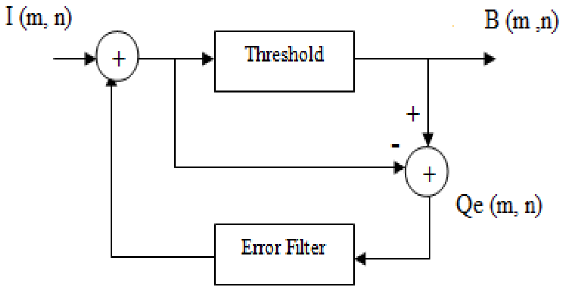


Figure 4. Floyd- Steinberg's error diffusion algorithm

2(b).ii. Stochastic error diffusion

Tiecheng used stochastic weights in place of fixed weights as used in Floyd- Steinberg method. In this approach there is less probability of occurrence of certain pattern like worms or other unwanted repeated texture in halftoned image [14]. He employed Gaussian process of error diffusion as the Gaussian distribution achieves maximum entropy over all other distributions for a given variance. Tiecheng used the concept of 'uniform error propagation' to compute the expectations of stochastic weights. By using the concept of 'Direct and Indirect impact' he derived the following values of expectations which are the stochastic weights to be used in the error diffusion equation (8).

$\mu_1 = 0.47243$ $\mu_2 = 0.03672$ $\mu_3 = 0.15684$ $\mu_4 = 0.15684$

2(b).iii. Five neighbor stochastic error diffusion (FNSED)

Abhinav, Vineet et al. [15] proposed to diffuse the quantization error to five neighboring pixels of a current pixel. This diffusion of error to five neighboring pixels resulted in better quality of halftones in terms of randomization of repeated patterns in the halftoned image whereas the patterns occurring with the above two methods of error diffusion repeat periodically. For a current pixel under processing at location (m, n), the positions of five neighboring pixels to which the error has to be diffused is shown in figure 5.

By using the concept of 'uniform error propagation' and 'Direct and Indirect Impact', the following values of expectations are obtained by this method which are used as stochastic weights in the error diffusion equation (8)

$\mu_1 = 0.5053 \quad \mu_2 = -0.062 \quad \mu_3 = 0.20190 \quad \mu_4 = 0.12891 \quad \mu_5 = 0.2260$

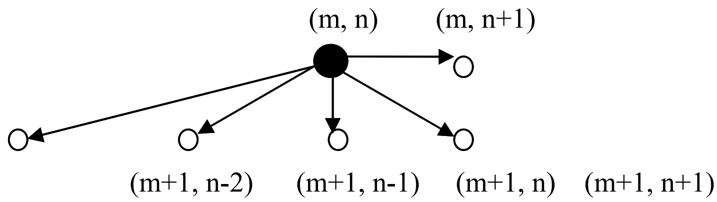


Figure 5. Pixel positions of five neighbors in FNSED

where the black circle denotes the current pixel under processing.

3. The proposed approach

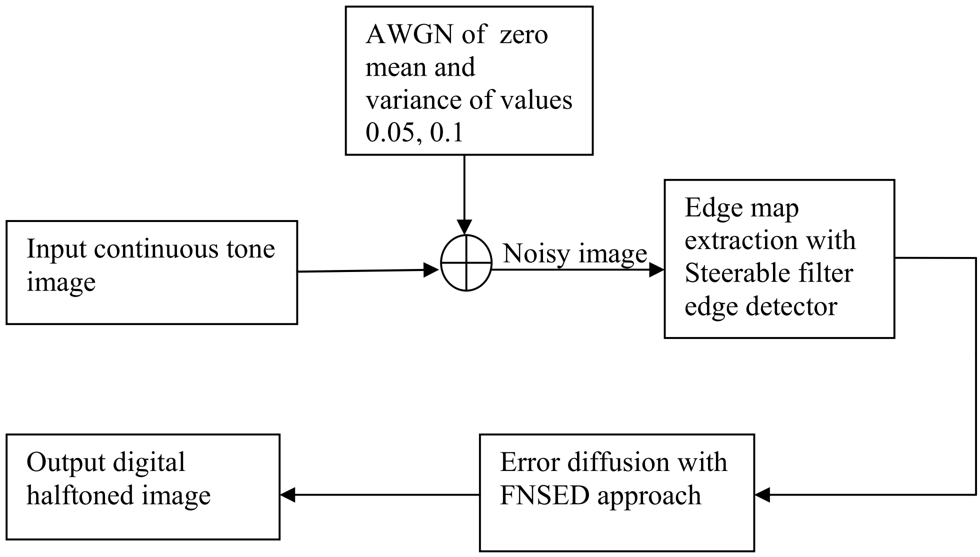


Figure 6. Block diagram of proposed SSED approach

Steerable stochastic error diffusion (SSED) is a hybrid scheme which utilizes the features of Steerable filter [12, 13] for detection of edges from a noisy image and FNSED [15] approach for error diffusion purpose to generate better quality halftones in presence of noise. Edges have great importance in the perception of halftoned image. Therefore to generate better quality halftones the edges need to be preserved in the halftoned image. This is done by extracting a binary edge map from the noisy image. In the work presented in this paper, the AWGN is mixed with the input image for two values of variance 0.05 and 0.1. The binary edge map from these noisy images is then extracted with the help of four methods of edge detection discussed in section 2 i.e. multi-scale morphological edge detection, Canny edge detection, Sobel edge detection, Steerable filter edge detection. The result of edge map extraction from noisy image with Steerable filter is better as compared to other three methods. Also the edge map obtained is continuous and there is no diffusion of error across edges implying that edges remain fully preserved. This edge map information obtained by Steerable filter then guides to stop the diffusion of error at edges. Three error diffusion algorithms discussed above in section 2 i.e.

Floyd- Steinberg algorithm, stochastic algorithm and five neighbor stochastic error diffusion (FNSED) are applied on these edge maps for diffusing the error to get the halftoned outputs.

One of the desirable features of any halftone is that the patterns occurring in the halftoned output due to error diffusion process should be randomized in nature and the patterns should not repeat periodically. In the FNSED approach proposed in [15] the authors show that the results of FNSED approach are comparatively better in terms of randomization of repeated patterns. Therefore FNSED approach when integrated with Steerable filter which is termed as SSED produced desirable quality halftones in the presence of noise. The block diagram shown in figure 6 depicts the working of proposed SSED approach.

4. Results

For an input of cameraman image, the digital halftoned outputs obtained with the edge maps generated by four edge detectors discussed above and three error diffusion algorithms in the presence of Gaussian noise of zero mean and variance of values 0.05 and 0.1 are shown in figures 7and 8 respectively. The arrows marked in figures 7.1 (c), (d) and (e) reveal the presence of noise (false edge detections) with the respective edge detection methods whereas such false detections are very few with Steerable edge detection method as seen in figure 7.1(f) and all subsequent figures.

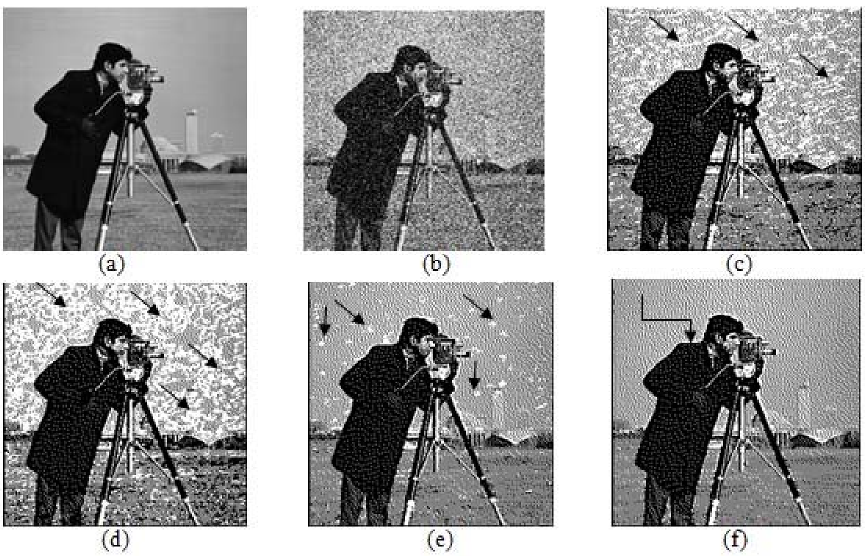


Figure 7.1. Digital halftones of (a) original cameraman image obtained with 0.05 value of variance (b) noisy image and using *FNSED* approach for error diffusion with (c) multiscalemorphological edge detector (d) Canny edge detector (e) Sobel edge detector (f) Steerable filter edge detector

The arrow marked in halftone of figure 7.2 (f) indicates that the Stochastic approach has taken that particular area as completely black whereas this area has gray values in the original image. The other two approaches of error diffusion i.e. FNSED and Floyd-Steinberg have taken this area as gray as seen by the white dots appearing due to halftoning process marked by arrows in 7.1 (f) and 7.3 (f) respectively. The same point is clearly visible in other halftones also as well.

The comparison of highlighted portions (shown by rectangular boxes) of figures 8.1(f), 8.2 (f), 8.3 (f) is shown in figures 9(a), (b), (c) respectively. From figure 9 (a), it is observed that the patterns formed due to error diffusion process of FNSED approach are randomized whereas the patterns formed in figures 9(b) and 9(c) due to error diffusion process of Stochastic and Floyd-Steinberg approaches respectively are having periodic repetition.

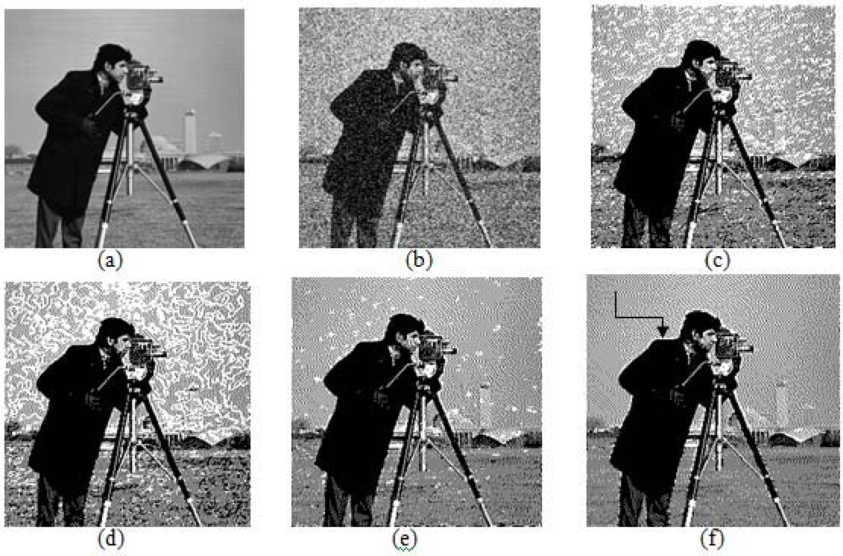


Figure 7.2. Digital halftones of (a) original cameraman image obtained with 0.05 value of variance (b) noisy image and using *Stochastic* approach for error diffusion with (c) multiscalemorphological edge detector (d) Canny edge detector (e) Sobel edge detector (f) Steerable filter edge detector

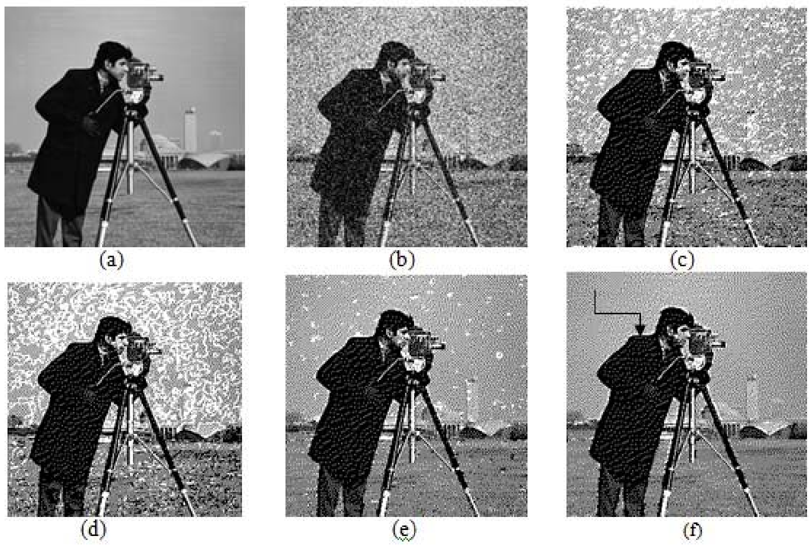


Figure 7.3. Digital halftones of (a) original cameraman image obtained with 0.05 value of variance (b) noisy image and using *Floyd-Steinberg's* approach for error diffusion with (c) multiscalemorphological edge detector (d) Canny edge detector (e) Sobel edge detector (f) Steerable filter edge detector

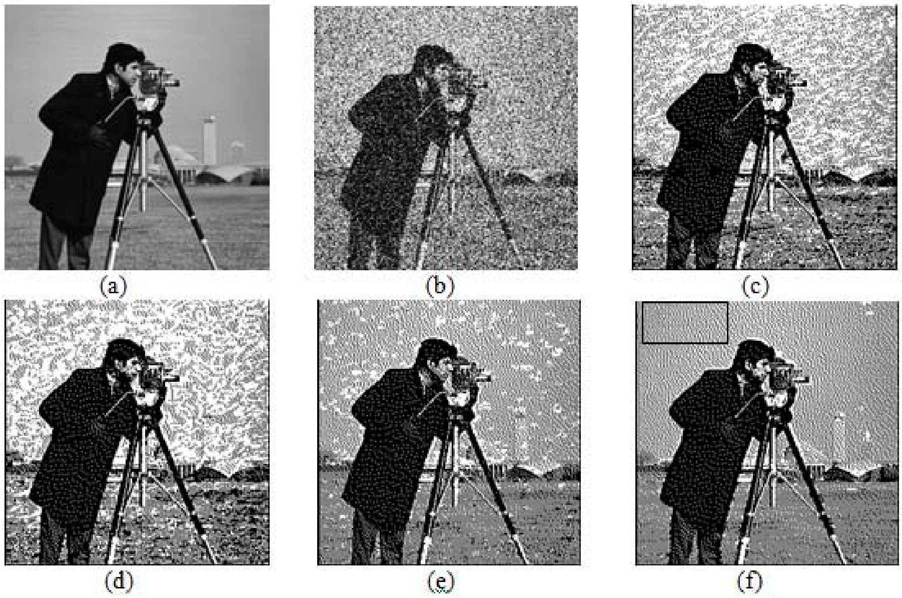


Figure 8.1. Digital halftones of (a) original cameraman image obtained with 0.1 value of variance (b) noisy image and using *FNSED* approach for error diffusion with (c) multiscalemorphological edge detector (d) Canny edge detector (e) Sobel edge detector (f) Steerable filter edge detector

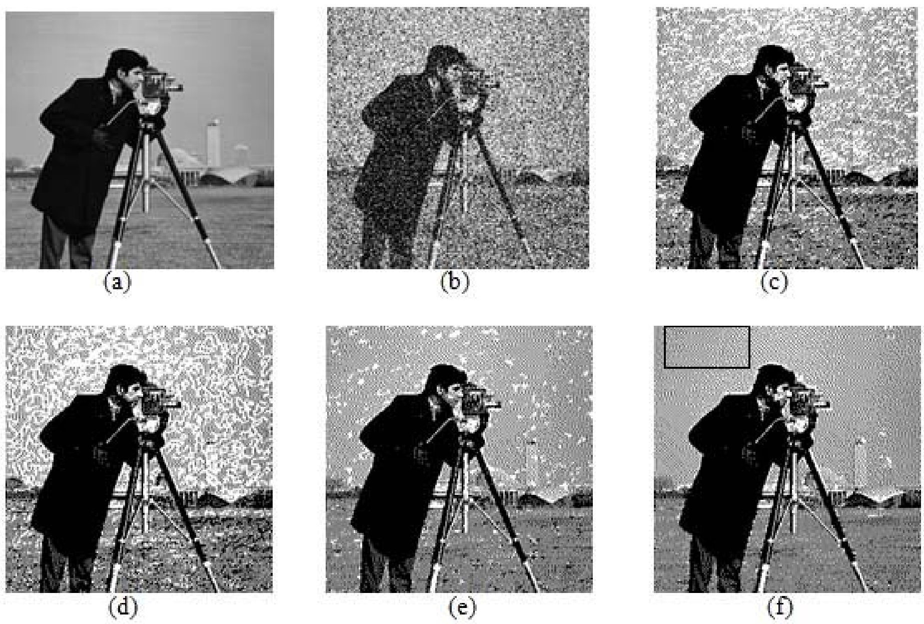


Figure 8.2. Digital halftones of (a) original cameraman image obtained with 0.1 value of variance (b) noisy image and using *Stochastic* approach for error diffusion with (c) multiscalemorphological edge detector (d) Canny edge detector (e) Sobel edge detector (f) Steerable filter edge detector

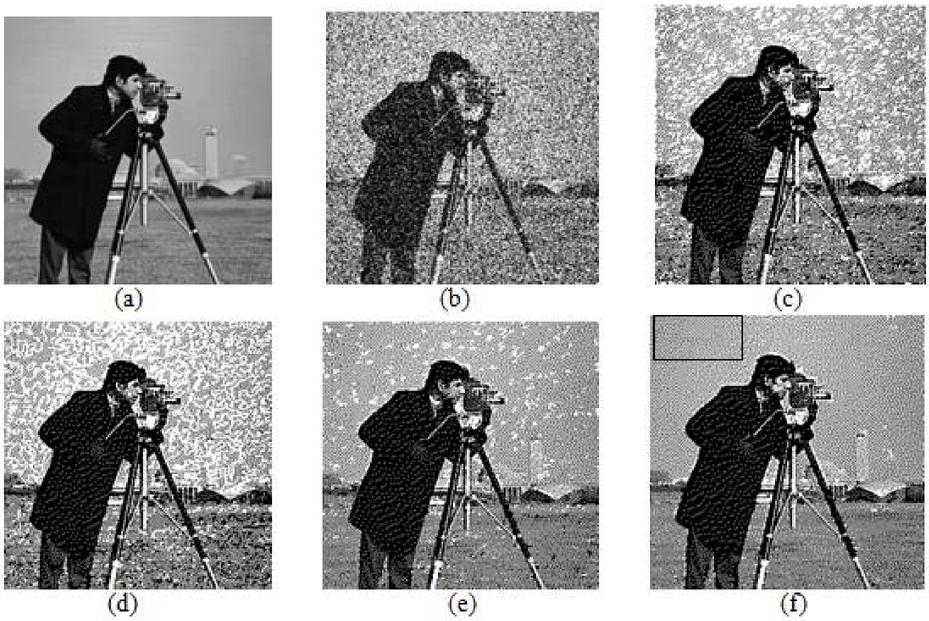


Figure 8.3. Digital halftones of (a) original cameraman image obtained with 0.1 value of variance (b) noisy image and using *Floyd-Steinberg's* approach for error diffusion with (c) multiscalemorphological edge detector (d) Canny edge detector (e) Sobel edge detector (f) Steerable filter edge detector

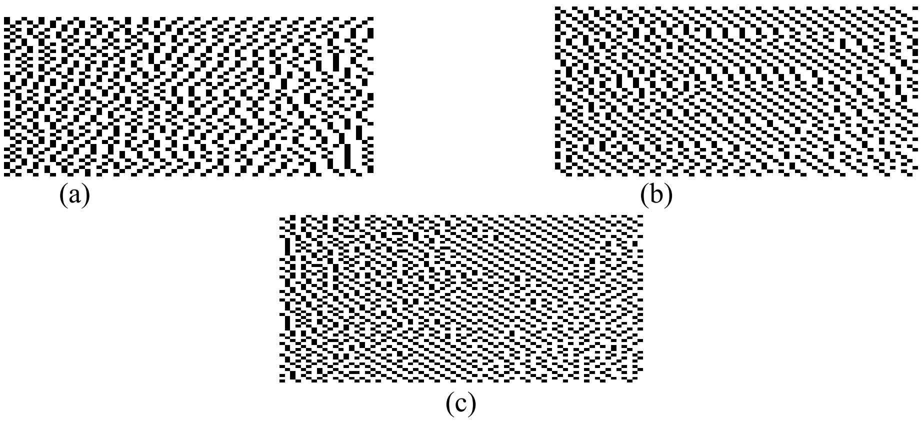


Figure 9. (a), (b, (c) Highlighted portions (shown by rectangular boxes) of figures 8.1(f), 8.2 (f), 8.3 (f) respectively

5. Conclusion

In this paper, both the edge detection and error diffusion concepts have been discussed in the presence of noise. The standard edge detection methods reported in literature have not taken into consideration the concept of error diffusion in the presence of noise. Similarly the error diffusion methods reported earlier have not considered the concept of edge detection in the presence of noise. In this paper, both the aspects have been combined to obtain better quality halftones in the presence of even high variance of noise.

As the halftones obtained with even high value of variance of Gaussian noise are having very few false edge detections with Steerable filter edge detector, it is concluded that the performance of this edge detector in presence of noise is better than the other three methods of edge detection discussed in the paper.

One of the desirable features of any halftone is that the patterns formed due to halftoning process should be randomized in nature and the patterns should not repeat periodically. This feature of randomization of repeated patterns of halftones is achieved with FNSED approach of error diffusion. It has been shown that the FNSED approach for error diffusion presented in this paper is better compared to other approaches. Further, the proposed approach of SSED which integrates the good features of Steerable filter edge detector for edge detection process and FNSED approach for error diffusion process produces desirable quality halftones in the presence of noise.

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