Edge Preserving Halftoning based on the Error Diffusion Technique

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論文摘要

本論文首先檢視誤差擴散技術，討論其優缺點。然後，提出一個誤差擴散演算法的修訂版來增強其效果。我們所提出的方法在誤差擴散處理後具有保持影像中物體邊緣輪廓的優點。在我們的實驗中新方法被應用到許多不同性質的影像且獲得不錯的預期結果。
關鍵詞：半色調、誤差擴散、邊緣偵測

Abstract

The error diffusion technique of the digital half-toning is examined. The shortcomings of this technique are discussed. Then, we propose a modified version of the error diffusion algorithm to improve its performance. The proposed method has the advantage that the edge contours in the given image are preserved after the error diffusion processing. Several experiments are given to show the performance of the proposed algorithm.
Keywords: Halftoning, Error Diffusion, Edge Detection

1. Introduction

Digital halftoning is a processing for generating images with limited number of gray levels. An excellent digital halftoning technique has to preserve the appearance of the original continuous-tone images. It can also be referred to as perceptually lossless image coding. The digital halftoning technique can find applications in the traditional paper printing and the new emerging LED display technology.

There have been a number of methods developed for digital halftoning, such as the thresholding, the dithering, and the error diffusion [1]. Recently, two major categories of model-based approach have been proposed: the human visual perception model [2]-[7] and the printer distortion model [8]-[10]. The human visual perception model is represented as a shift-invariant linear FIR filter, specified by the sampling spacing and the viewing distance between the eye and the paper. The printer distortion model is defined in terms of the radius of printer dots, and implemented as a look-up table according to local configuration of binary pixel values.

In the Nishida's work [7], the human visual perception with respect to spatial frequency is modeled as a two-dimensional shift-invariant linear FIR lowpass filter with a smooth transition band. The digital halftone image is designed to minimize the error between the FIR filtering results of the original and the halftone image in the least-square sense. Experimental results of different scales are provided. Compare the results of different scales, we find that they are undistinguishable except for the edges are getting clearer while the scale increasing.

In this research, we study the traditional halftoning techniques of the thresholding, the dithering, and the error diffusion. Quantitative errors of these techniques are evaluated and discussed. We will show that the thresholding technique has the smallest mean square error. However, the error diffusion technique has the smallest mean square error after applying a small moving average filter. This phenomenon confirms the human perceptual model proposed by the early researchers.

By incorporating the properties obtained in our study and the Nishida's work, we propose an edge preserving halftoning method based on the error diffusion technique. The proposed method has the advantages of the error diffusion at smooth image regions and the edge preserving at the shape boundaries. The proposed algorithm is simple, efficient, and gives perceptually pleasant halftone images.

In addition, we present an edge enhancing version of the new method. The edge enhancing version gives a hard constraint that all edge pixels should be set to zero in the resulting halftone image. We will show that the edge enhanced halftoning gives satisfactory results for some particular types of images.

This paper is organized as follows. The traditional halftoning techniques of the thresholding, the dithering, and the error diffusion are introduced in section 2. Quantitative errors of these techniques are evaluated and discussed. The proposed edge preserving halftoning technique is given in section 3. The edge enhancing halftoning algorithm is given in section 4. Experimental results are provided in section 5. Conclusions are presented in section 6.

2. Evaluation of the traditional methods

In this section, we introduce the traditional halftoning techniques of the thresholding, the dithering, and the error diffusion. Then, their performance are evaluated and compared.

2.1 The thresholding technique

The thresholding technique is the most straightforward way of halftoning. Figure 1 gives the grayscale mapping function of a 4-grayscale uniform thresholding example. The method is simple, efficient, and provides a minimum mean-square-error halftone image.

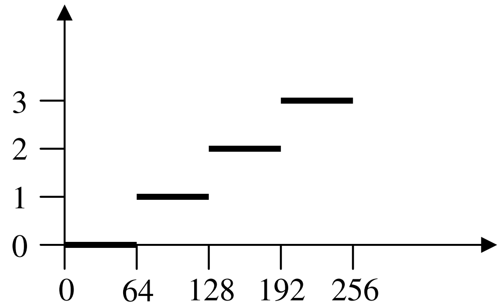

Figure 1 The mapping function of a 4-grayscale uniform thresholding.

2.2 The dithering technique

The dithering technique is to compare the given image with the repeated dithering matrix. Two typical dithering matrices are as bellow.

$$D_1 = \begin{bmatrix} 0 & 128 \\ 192 & 64 \end{bmatrix}$$

$$D_2 = \begin{bmatrix} 0 & 128 & 32 & 160 \\ 192 & 64 & 224 & 96 \\ 48 & 176 & 16 & 144 \\ 240 & 112 & 208 & 80 \end{bmatrix}$$

Suppose d(i,j) is the matrix obtained by replicating D. Thus an output pixel p(i,j) is defined by

$$p(i,j) = \begin{cases} 1 & \text{if } x(i,j) > d(i,j) \\ 0 & \text{if } x(i,j) \le d(i,j) \end{cases}$$

Due to the random nature of the dithering matrix, it does not produce false contours as in the thresholding technique.

2.3 The error diffusion technique

The error diffusion technique distributes the quantization error of each pixel into its neighbors. Three different schemes are applicable for error diffusion. They are the Floyd-Steinberg scheme, the Jarvis-Judice-Ninke scheme, and the Stucki scheme. Their corresponding masks are given as follows.

	x	+7/16E
+3/16E	+5/16E	+1/16E

Figure 2 The Floyd-Steinberg error diffusion mask.

		x	+7/48E	+5/48E
+3/48E	+5/48E	+7/48E	+5/48E	+3/48E
+1/48E	+3/48E	+5/48E	+3/48E	+1/48E

Figure 3 The Jarvis-Judice-Ninke error diffusion mask.

		x	+8/42E	+4/42E
+2/42E	+4/42E	+8/42E	+4/42E	+2/42E
+1/42E	+2/42E	+4/42E	+2/42E	+1/42E

Figure 4 The Stucki error diffusion mask.

The error diffusion technique has the special property that its local quantization error sum is zero.

2.4 Evaluation and comparison

A gray level image caribou.tif is shown in Figure 5(a), which is obtained from the website of [1]. The digital halftone image produce by the thresholding, the dithering, and the error diffusion techniques are shown in Figure 5(b), 5(c), and 5(d) respectively. The dithering and error diffusion techniques produce more satisfactory results for human eyes.

Figure 5(a) The original gray level image caribou.tif.

Figure 5(b) The halftone image of (a) produced by bi-level thresholding.

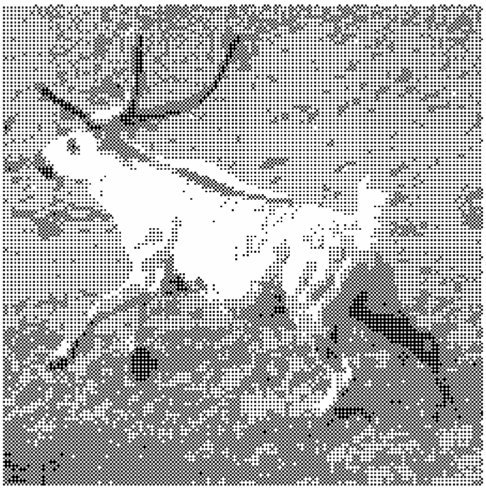

Figure 5(c) The image produced by dithering.

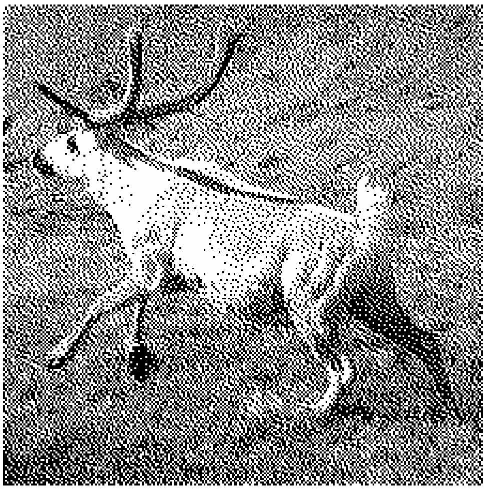

Figure 5(d) The image produced by error diffusion.

To get the quantitative characteristic of these halftone images, the root-mean-square error with respect to the original image for different techniques are computed and plotted in Figure 6. The horizontal axis represents the number of gray-levels used in the halftone image. The lowest one is the thresholding technique that is very different from the human perspective.

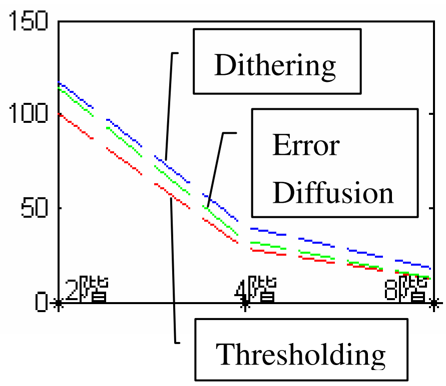

Figure 6 The root-mean-square error of the three traditional techniques with respect to different number of final gray levels.

To further examine the difference between the quantitative evaluation and the human perspective. Referring to the previous researchers' human eye model, the human eyes are modeled by a low-pass filter with a proper bandwidth and a smooth transition band. To simulate the human visual system, we take the simplest lowpass filter of the local averaging. We take a 3x3 local averaging and then re-calculate the root-mean-square error of each halftone image. The results are plotted in Figure 7. An interesting result is found that the quantitative measurement shown in Figure 7 coincides with the human qualitative perspective.

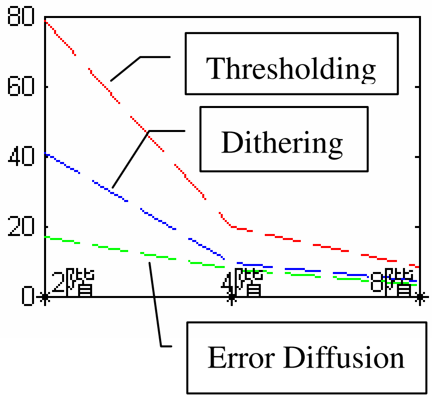

Figure 7 The root-mean-square error evaluated after a 3x3 average filtering.

The magic of the dithering and the error diffusion is that the halftone images produced by these techniques successfully fit the original image after a lowpass filtering. Thus, the human eyes are cheated.

3. The proposed algorithms

The error diffusion technique suffers from a problem that the edges in the original image are almost destroyed after halftoning. Edges are important features in the human vision. We recognize an object by its shape which is formed by the edges in its image. A careful observation will find that the sharp edges in Figure 5(a) can not be found in Figure 5(d). Edge information is destroyed by the error diffusion process. Thus, it is hard to recover the shape details from the halftone image.

In this research, we try to preserve the edges in the original image in the error diffusion process. Two algorithms are designed based on this concept. The proposed algorithms are as follows.

3.1 The edge preserving halftoning

Edge preserving halftoning algorithm

1. Apply the Canny edge detector [11] to obtain an edge map.

$$c(i,j)=\begin{cases}1 & \text{for background pixels}\\ 0 & \text{for edge pixels}\end{cases}$$

2. For each pixel, perform the steps 3-5.
3. Perform the quantization by

$$p(i,j)=\begin{cases}0 & \text{if } x(i,j)<128\\ 255 & \text{if } x(i,j)\geq 128\end{cases}$$

where x(i,j) is the original image and p(i,j) is the quantized image.

4. Calculate the quantization error by

$$E=\begin{cases}x(i,j) & \text{if } x(i,j)<128\\ x(i,j)-255 & \text{if } x(i,j)\geq 128\end{cases}$$

5. Spread the error E to update x(i,j) by applying the modified Stucki mask.

		X	+8cE/S	+4cE/S
+2cE/S	+4cE/S	+8cE/S	+4cE/S	+2cE/S
+1cE/S	+2cE/S	+4cE/S	+2cE/S	+1cE/S

where c is the edge map value of the corresponding pixel and S is the sum of the coefficients which may vary with the edge map c.

To illustrate the effect of the modified Stucki mask, let's consider the following example edge map.

1	1	1	0	1	1
1	1	1	0	0	1
1	1	x	1	0	1
1	1	0	0	1	1
1	0	1	1	1	1
0	1	1	1	1	1

The pixel under processing is marked by x. According to the edge map values, we can construct the modified Stucki mask of the x pixel as follows.

		X	+8E/24	0
+2E/24	+4E/24	0	0	+2E/24
+1E/24	0	+4E/24	+2E/24	+1E/24

In this way, the quantization error can be diffused across the edges while the edge pixel values are not changed. The error value is diffused according to the same distance weighting with the Stucki mask. The sum of the weighting coefficients S in this case is 24.

The Canny edge detector applied in this algorithm has the following properties. [1]

1. Low error rate of detection. It should find all edges and nothing but edges.
2. Localization of edges. The distance between actual edges in the image and edges found by this algorithm should be minimized.
3. Single response. The algorithm should not return multiple edge pixels when only a single edge exists.

Due to property 3, the edges obtained by the Canny's algorithm have only one pixel width. Omit a few edge pixels will not reduce the performance of the error diffusion process, because its effect is on a lower resolution level. However, the preserved edges give a great help for the shape recognition of the human vision.

3.2 The edge enhancing halftoning

Edge enhancement is a well known technique to make the edges in an image sharper and crisper, which generally results in an image more pleasing to the human eye. The unsharp masking and the high-boost filtering are two example techniques to process the gray level images. Based on the idea of the edge enhancement techniques, we develop an edge enhancing halftoning algorithm as follows.

Edge enhancing halftoning algorithm

1. Apply the Canny edge detector [11] to obtain an edge map.

$$c(i,j)=\begin{cases}1 & \text{for background pixels}\\ 0 & \text{for edge pixels}\end{cases}$$

2. For each pixel, perform the steps 3-6.
3. Perform the quantization by

$$p(i,j)=\begin{cases}0 & \text{if } x(i,j)<128\\ 255 & \text{if } x(i,j)\geq 128\end{cases}$$

where x(i,j) is the original image and p(i,j) is the quantized image.

4. Enhance the edge pixels by

$p(i,j)=0$ if $c(i,j)=0$

5. Calculate the quantization error by

$E=x(i,j)-p(i,j)$

6. Spread the error E to update x(i,j) by applying the original Stucki mask.

		x	+8/42E	+4/42E
+2/42E	+4/42E	+8/42E	+4/42E	+2/42E
+1/42E	+2/42E	+4/42E	+2/42E	+1/42E

Referring to the step 4, we enhance the edge pixels by painting them to black in the halftone image. Again, the pixel level processing will not reduce the performance of the error diffusion. In addition, we do not need to preserve the original value of the edge pixels this time, because we will paint them to black in the later steps. Therefore, the error spreading mask is back to the original version.

4. Experimental results

The images used in our experiments are provided by the website of [1]. In our experiments, we compare the performance of the Stucki's method, the proposed edge preserving algorithm and the proposed edge enhancing algorithm.

Figure 8(a) is the original image cameraman.tif. The edge image produced by the Canny's edge detection algorithm is shown in Figure 8(b). As shown in the figure, the edge lines produced by the Canny's algorithm are of one single pixel width. The halftone image produced by the Stucki's method is shown in Figure 8(c). The edge preserved halftone image and the edge enhanced halftone image produced by our algorithms are shown in Figure 8(d) and 8(e) respectively. Comparing Figure 8(c) and 8(d), the details of the background buildings are clearer in the edge preserved version. Although the edges are enhanced in Figure 8(e), some false contours are presented.

Figure 8(a) The original image cameraman.tif.

Figure 8(b) The edge image produced by the Canny's edge detection algorithm.

Figure 8(c) The halftone image produced by the Stucki's method.

Figure 8(d) The edge preserved halftone image produced by our algorithm.

Figure 8(e) The edge enhanced halftone image produced by our algorithm.

Figure 9(a) is the original image caribou.tif. The edge image produced by the Canny's edge detection algorithm is shown in Figure 9(b). As shown in the figure, the edge lines produced by the Canny's algorithm are of one single pixel width. The halftone image produced by the Stucki's method is shown in Figure 9(c). The edge preserved halftone image and the edge enhanced halftone image produced by our algorithms are shown in Figure 9(d) and 9(e) respectively. Comparing Figure 9(c) and 9(d), the boundary lines of the caribou are clearer in the edge preserved version. Although the edges are enhanced in Figure 9(e), some false contours are presented especially on the grassed ground.

Figure 9(a) The original image caribou.tif.

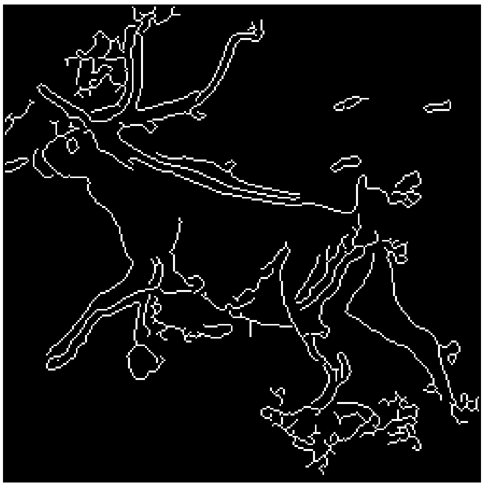

Figure 9(b) The edge image produced by the Canny's edge detection algorithm.

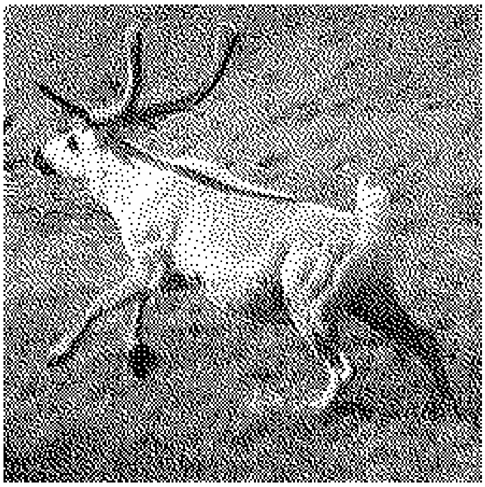

Figure 9(c) The halftone image produced by the Stucki's method.

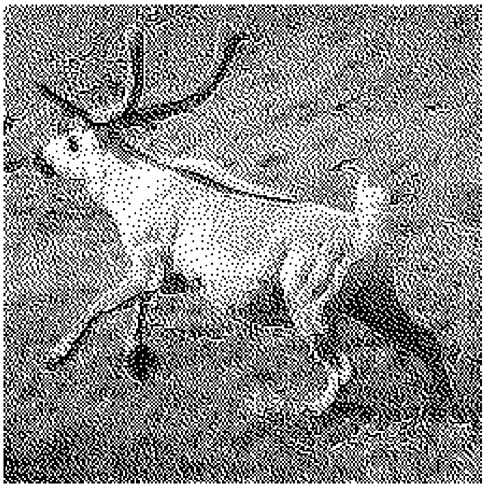

Figure 9(d) The edge preserved halftone image produced by our algorithm.

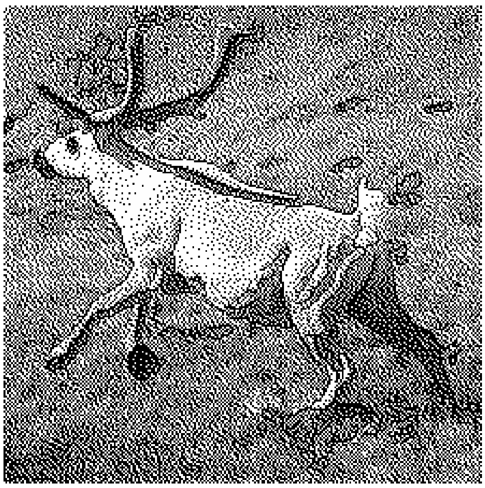

Figure 9(e) The edge enhanced halftone image produced by our algorithm.

Figure 10(a) is the original image ic.tif. The edge image produced by the Canny's edge detection algorithm is shown in Figure 10(b). As shown in the figure, the edge lines produced by the Canny's algorithm are of one single pixel width. The halftone image produced by the Stucki's method is shown in Figure 10(c). The edge preserved halftone image and the edge enhanced halftone image produced by our algorithms are shown in Figure 10(d) and 10(e) respectively. The IC is a man-made product, which formed mostly by straight lines and flat planes. Comparing Figure 10(c), 10(d), and 10(e), the edge enhanced version 10(e) is the best among all.

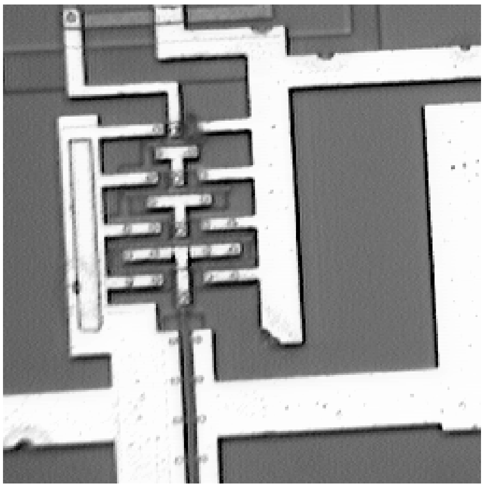

Figure 10(a) The original image ic.tif.

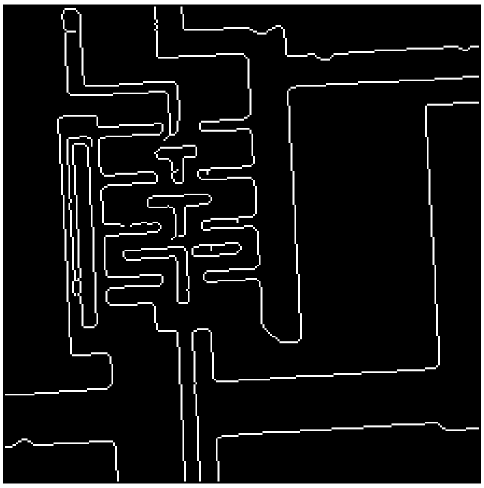

Figure 10(b) The edge image produced by the Canny's edge detection algorithm.

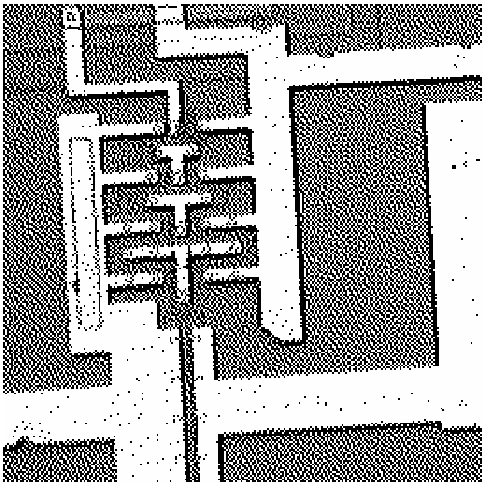

Figure 10(c) The halftone image produced by the Stucki's method.

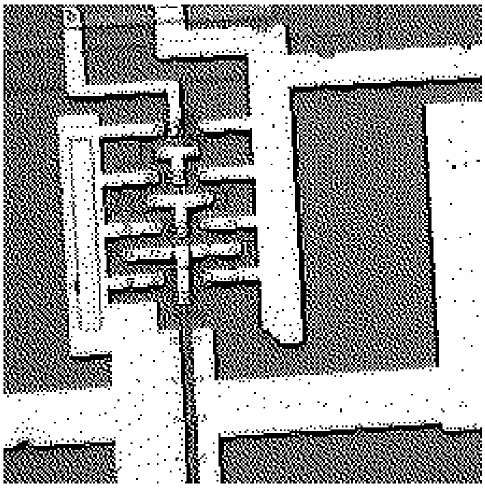

Figure 10(d) The edge preserved halftone image produced by our algorithm.

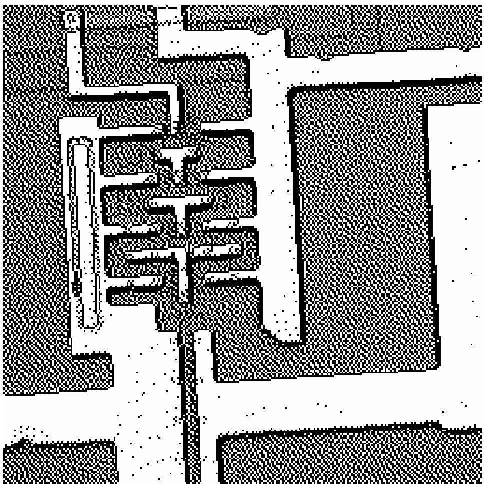

Figure 10(e) The edge enhanced halftone image produced by our algorithm.

Figure 11(a) is the original image rice.tif. The edge image produced by the Canny's edge detection algorithm is shown in Figure 11(b). As shown in the figure, the edge lines produced by the Canny's algorithm are of one single pixel width. The halftone image produced by the Stucki's method is shown in Figure 11(c). The edge preserved halftone image and the edge enhanced halftone image produced by our algorithms are shown in Figure 11(d) and 11(e) respectively. The rice image in Figure 11(a) has simple boundaries and the image background is clear. The edge image in Figure 11(b) is very perfect. Therefore, the edge enhanced halftone image Figure 11(e) produced by the proposed edge enhancing algorithm is very pleasing to human eye. Figure 11(d) is the secondary one and Figure 11(c) is the worst.

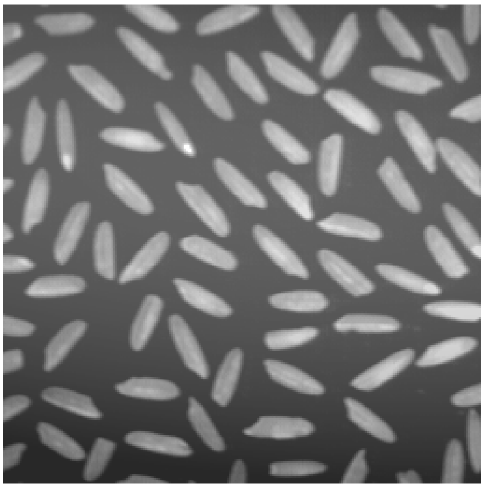

Figure 11(a) The original image rice.tif.

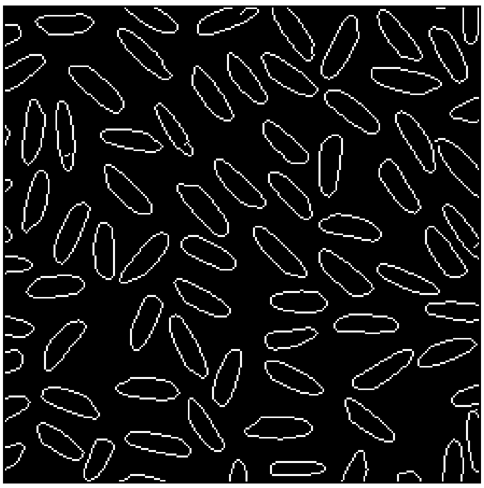

Figure 11(b) The edge image produced by the Canny's edge detection algorithm.

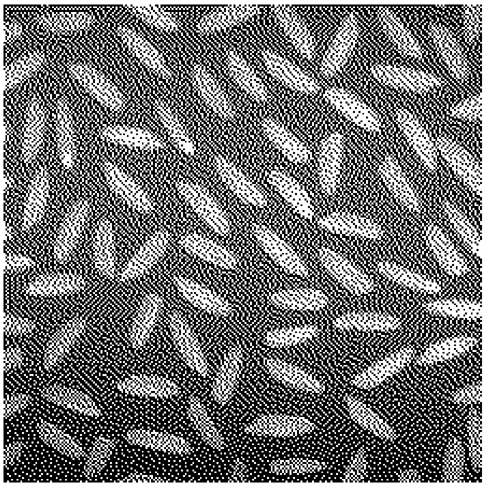

Figure 11(c) The halftone image produced by the Stucki's method.

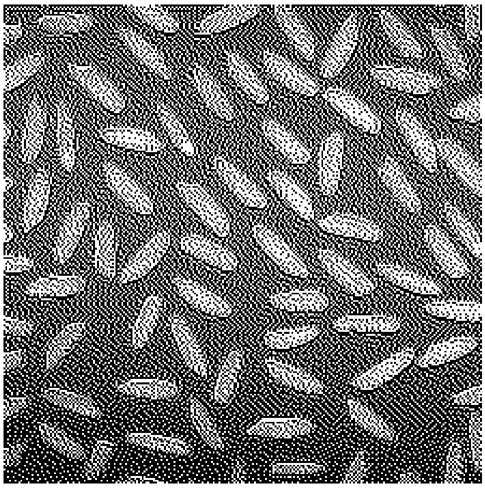

Figure 11(d) The edge preserved halftone image produced by our algorithm.

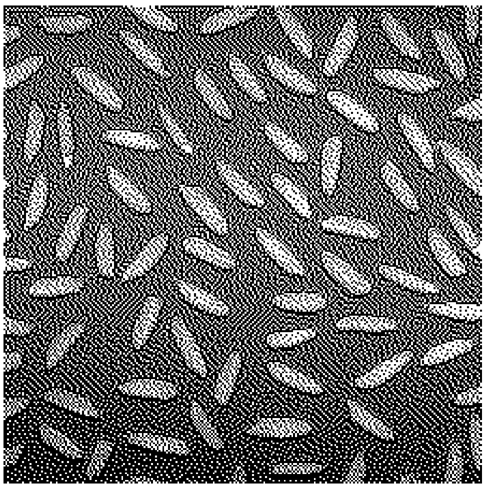

Figure 11(e) The edge enhanced halftone image produced by our algorithm.

5. Conclusions

In this paper, we examine the properties of the error diffusion halftoning technique. Then, an edge preserving and an edge enhancing versions are proposed. The new proposed algorithms have the advantages of the error diffusion technique. In addition, the edges are preserved or enhanced to produce a more pleasing halftone image.

Experimental results show that the halftone images produced by our algorithms are clearer in image details and are more pleasing to human eye. In the cases that the Canny's algorithm obtains good edge images, the edge enhancing error diffusion algorithm produces can very good halftone images. In the other cases, the edge enhancing version produces false contours. Thus, the edge preserving version is a better choice.

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