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CONTRAST ENHANCEMENT USING MODIFIED ERROR DIFFUSION

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ABSTRACT

This paper proposes a contrast enhancement (CE) algorithm combined with modified error diffusion (ED). After simple histogram equalization (HE), artefacts such as false contours are produced in the enhanced image. The proposed CE algorithm using modified ED consists of two parts: CE and ED. In the first part, a low-contrast input image is enhanced by the conventional HE method. In the second part, we use the modified ED algorithm. The inputs of the second part are the average and scaled difference images of the original input image and the HE image, in which the scaled difference image is diffused by the ED algorithm. In the proposed algorithm, the modified ED algorithm reduces the artefact produced in the HE image, and increases the number of intensity grey levels. Computer simulations with a number of low-contrast images show the effectiveness of the proposed CE method in terms of the visual quality as well as the probability mass function. It can be used as a post-processing for CE with simultaneous artefact reduction in various display devices.

1. INTRODUCTION

In most digital display devices, decoded or degraded images are enhanced by a post-processing such as contrast enhancement (CE), detail enhancement, noise or artefact reduction, and so on. Previous works on CE include simple histogram equalization (HE) [1, 2], Velde's method [3], Nilsson *et al.*'s method [4], and so on. Nilsson *et al*.'s method uses the successive mean quantization transform (SMQT) for automatic enhancement of greyscale image [4]. After CE, the high-contrast image is obtained from a low-contrast image, however the artefacts such as false contours and ringing artefacts are generated. The artefact reduction algorithms are applied to the images containing artefacts, which are enhanced by the CE algorithm [5, 6]. Therefore, most post-processing methods in digital display devices consist of two parts: CE and artefact reduction. We propose a CE algorithm combined with modified error diffusion (ED), which simultaneously performs CE and artefact reduction. As simple CE, HE stretches the dynamic range of a low-contrast image and maintains the number of grey levels. By HE, the pixels which have the same grey level in the input image are mapped all together to the pixels which have the other same grey level in the enhanced image, with the number of grey levels unchanged. Thus, the artefacts such as false contours are produced in the enhanced image after simple HE if the number of grey levels is too small to faithfully describe the details of the image. The proposed CE algorithm uses the modified ED method to reduce the artefact. The conventional ED algorithm has been used to generate a greyscale image on a computer monitor, an ink-jet or electrophotographic printer, or other bi-level displays. The standard ED algorithm is a method that thresholds the pixel's original intensity level and diffuses the difference between the original intensity value and the thresholded intensity value [7–9]. The ED algorithms can be used to preserve and enhance detail components such as the edges and texture [10–12].

The proposed algorithm consists of two parts: CE and modified ED. In the first part, we use the simple HE method. In the second part, we apply the ED to the image enhanced by the HE method. The difference between the original input image and the HE image is scaled and considered as the signal to be diffused by the ED algorithm [7–9]. Thus, the number of grey levels is increased by the diffused scaled difference signal, which is the enhanced value in the first part of the proposed algorithm. The quantizer (Q) in the second part changes the bit depth of the output image. The bit depth of the output image is larger than or equal to that of the original input image.

The rest of the paper is organized as follows. In Section 2, the conventional ED is described. In Section 3, we propose a CE algorithm combined with modified ED. We show the effectiveness of the proposed CE algorithm for low-contrast images or images with the reduced bit depth. Experimental results with three low-contrast test images are presented in Section 4, showing the effectiveness of the proposed algorithm. In Section 5, we conclude the paper.

2. CONVENTIONAL ED

An ED method was first introduced by Floyd and Steinberg [7] in 1975. A large number of ED methods have been developed and used in various fields of image processing, computer vision, and graphics. Especially, ED is a technique which is used to display an image on a printer that represents continuous tone as the binary elements. This image is called the dithered image.

Figure 1(a) shows the block diagram of the conventional ED method. The intensity level of an input image $I(x, y)$, the continuous tone digital image, is compared with a fixed

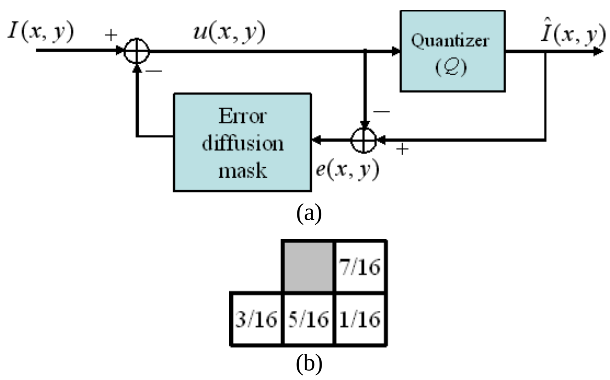

Figure 1 – Conventional ED method [7]. (a) block diagram, (b) coefficients of the Floyd and Steinberg's ED mask.

threshold in the quantizer $Q[\cdot]$. The difference between the state variable and the quantizer output is the quantization error $e(x, y)$. To represent the effect of the continuous tone, the quantization error is diffused to the four neighbouring pixels using the coefficients of the ED mask. Figure 1(b) shows the coefficients of the diffusion mask, for example, of the Floyd and Steinberg's ED mask, in which the grey-colour block is the current pixel to be processed. The error at the current pixel is multiplied by the coefficients of the ED mask and diffused to the four neighbouring pixels. The conventional ED method is expressed as

$$u(x,y) = I(x,y) - \sum_{(m,n)\in N} h(m,n)e(x-m, y-n) \tag{1}$$

$$\hat{I}(x,y) = Q[u(x,y)] = \begin{cases} L-1, & u(x,y) \ge \dfrac{L}{2} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$e(x,y) = \hat{I}(x,y) - u(x,y) \tag{3}$$

where $u(x, y)$ denotes the state variable at (x, y), $h(x, y)$ and $e(x, y)$ represent the coefficient of the ED mask and quantization error, respectively, N is the set of neighbouring pixels, and L is the total number of discrete grey levels of the input image (L: even). In general, the output image $\hat{I}$ is the binary image. In Eq. (1), the coefficient of the ED mask $h(x, y)$ can be replaced by the Jarvis-Roberts' [8] or Stucki's masks [9], which improves the quality of the dithered image. For example, in an image quantized to 8 bits, i.e., L=256, Eq. (2) compares the state variable $u(x, y)$ at the current pixel, which is represented by the integer between 0 and 255, with the fixed threshold $\frac{L}{2}$, i.e., 128. If the state variable is greater than the threshold, the output is set to L–1, otherwise to zero. In the proposed algorithm, the output of the modified ED method is multi-level rather than bi-level.

3. PROPOSED CE ALGORITHM

In the proposed CE algorithm, we apply the modified ED. The diffused signal by ED is the difference between the original input image and the enhanced image. In the proposed CE algorithm, the scaled difference signal is considered as the quantization error which is diffused by the ED algorithm.

Figure 2 shows the block diagram of the proposed CE algorithm combined with the modified ED method. In the first part of the proposed algorithm, the input (low-contrast) image is enhanced by the HE method. In the second part, we apply the modified ED algorithm. The inputs of the second part are the average $\bar{I}$ and one-half the difference ΔI (scaled difference), where the difference between the original input image and the enhanced image is considered as the scaled signal to be diffused by the ED algorithm. The average image and scaled difference image are defined, respectively, as

$$\bar{I}(x,y) = \frac{\tilde{I}(x,y) + I(x,y)}{2} \tag{4}$$

$$\Delta I(x,y) = \frac{\tilde{I}(x,y) - I(x,y)}{2} \tag{5}$$

where $I(x, y)$ signifies the input image and $\tilde{I}(x, y)$ represents the image enhanced by the HE method.

The modified ED algorithm is defined as

$$e(x,y) = \hat{I}(x,y) - I'(x,y) \tag{6}$$

$$I'(x,y) = \bar{I}(x,y) - \sum_{(m,n)\in N} h(m,n)e(x-m, y-n) \tag{7}$$

$$\tilde{I}'(x,y) = I'(x,y) + \Delta I(x,y) \tag{8}$$

$$\hat{I}(x,y) = Q[\tilde{I}'(x,y)] \tag{9}$$

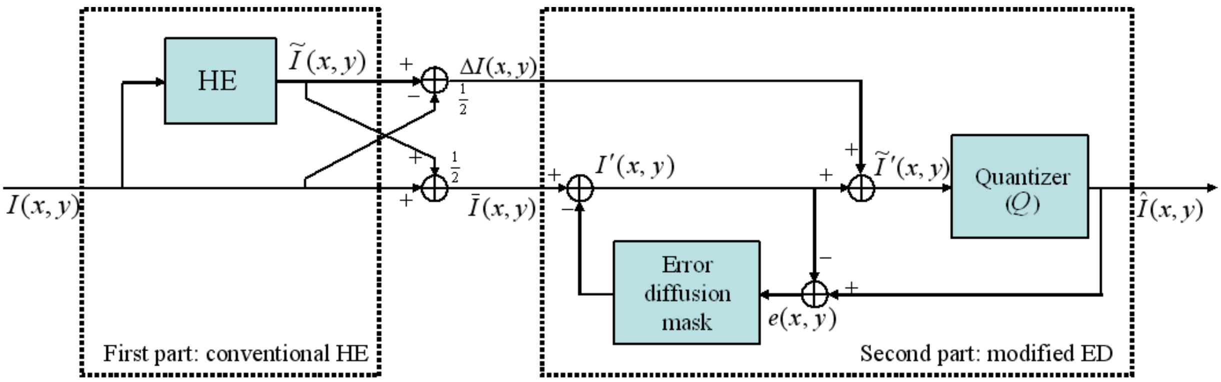

Figure 2 – Block diagram of the proposed CE algorithm combined with the modified ED method.

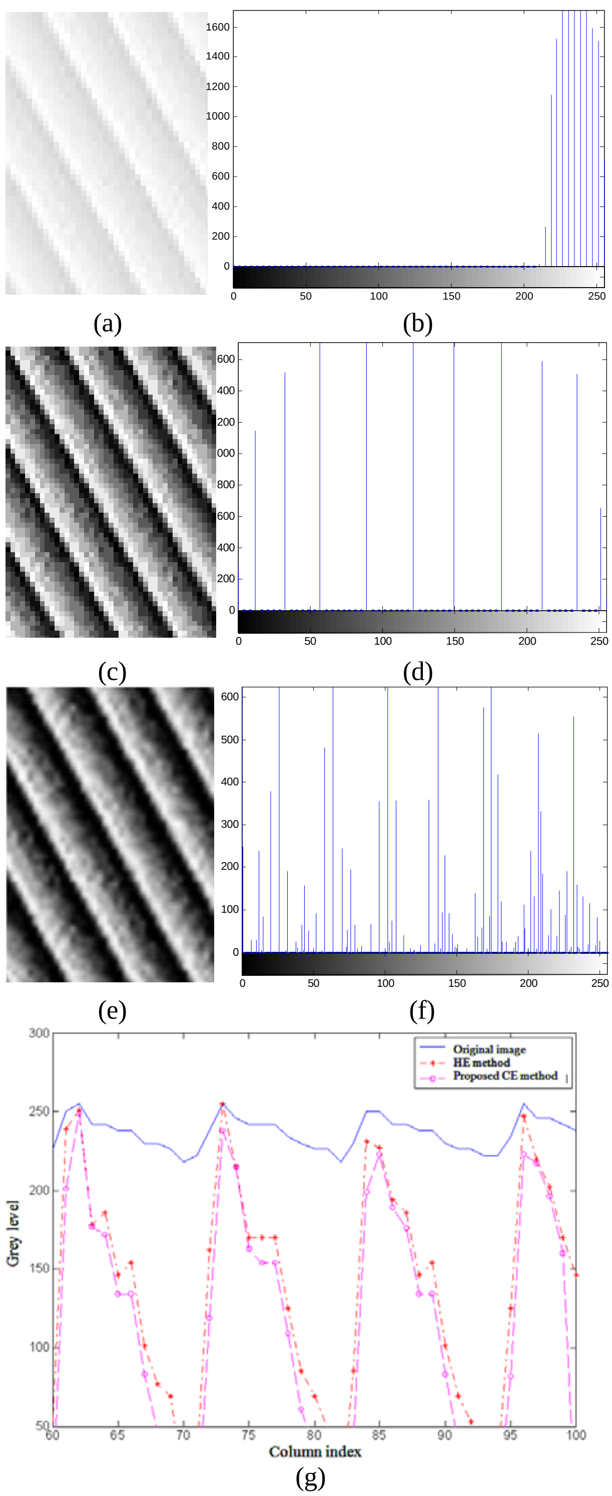

Figure 3 – Performance comparison of the proposed CE method for a low-contrast image with the reduced bit depth. (a) original image (6-bit depth), (b) histogram of (a), (c) HE image (8-bit depth), (d) histogram of (c), (e) enhanced image using the proposed CE method (8-bit depth), (f) histogram of (e), (g) 1-D intensity profile along the 80th row.

where $e(x, y)$ denotes the difference signal which is diffused by the ED algorithm, $I'(x, y)$ represents the state variable at (x, y), and $\tilde{I}'(x, y)$ signifies the image which is to be quantized by the quantizer $Q[\cdot]$. In the proposed method, the grey level of the output image is multi-level (with 8-, 7-, or 6-bit depth). The proposed CE algorithm can control the bit depth of the output image by the number of the quantization levels in the quantizer (Q). The number of grey levels of the output image is increased by diffusing the difference signals in the ED mask.

Figure 3 shows the performance comparison of the proposed CE method for a low-contrast image with the reduced bit depth. Figure 3(a) shows a 6-bit depth original image (100×170) which is bright and has very poor dynamic range. Figure 3(b) shows the histogram of Figure 3(a) which is mainly distributed in a limited range of high grey levels. Figure 3(c) illustrates the HE image (8-bit depth) of Figure 3(a). Figure 3(d) shows the histogram of Figure 3(c). The actual number of grey levels used in Figure 3(d) is the same as that used in Figure 3(b), noting that the HE method maintains the number of grey levels. The pixels which have the same grey level in the original image are mapped all together to the pixels which have the other same grey level in the enhanced image. Figure 3(c) shows false contours in relatively uniform regions, since the number of grey levels is not enough to effectively describe the texture. Figures 3(e) shows the image enhanced by the proposed CE algorithm (8-bit depth). Figure 3(f) illustrates the histogram of Figure 3(e). The actual number of grey levels used is increased by the ED mask of the proposed CE method, thus faithfully representing texture with false contours reduced. Figure 3(g) illustrates the performance comparison of the HE and proposed CE methods, in which a one-dimensional (1-D) intensity profile along the 80th row is shown. The curve of the HE method is step-shaped, whereas that of the proposed CE method is smooth because of the modified ED.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section, we demonstrate the effectiveness of the proposed CE algorithm combined with the modified ED method. Experimental results with three test images show that the proposed CE algorithm enhances better low-contrast images than the HE algorithm and SMQT method [4].

Figure 4 shows the comparison of the resultant images and histograms enhanced by the HE, SMQT, and proposed CE methods. Figure 4(a) shows the low-contrast test image 1 (500×500, 8-bit depth) obtained by the scanning electron microscope [1]. It is bright and has very poor dynamic range. Figure 4(b) shows the image enhanced by the HE method. Figure 4(c) shows the image enhanced by the SMQT method [4] whereas Figure 4(d) shows the image enhanced by the proposed CE algorithm. Figure 4(e) illustrates the histogram of Figure 4(a), which is mainly distributed in a limited range of high grey levels. Figures 4(f), 4(g), and 4(h) show the histograms of Figures 4(b), 4(c), and 4(d), which are enhanced by the HE, SMQT, and proposed CE methods, respectively. Note that the histogram of the proposed algorithm (Figure 4(h)) is flatter than those of the HE method (Figure 4(f)) and SMQT method (Figure 4(g)), i.e., the probability mass function, which is the normalized histogram, of the proposed CE

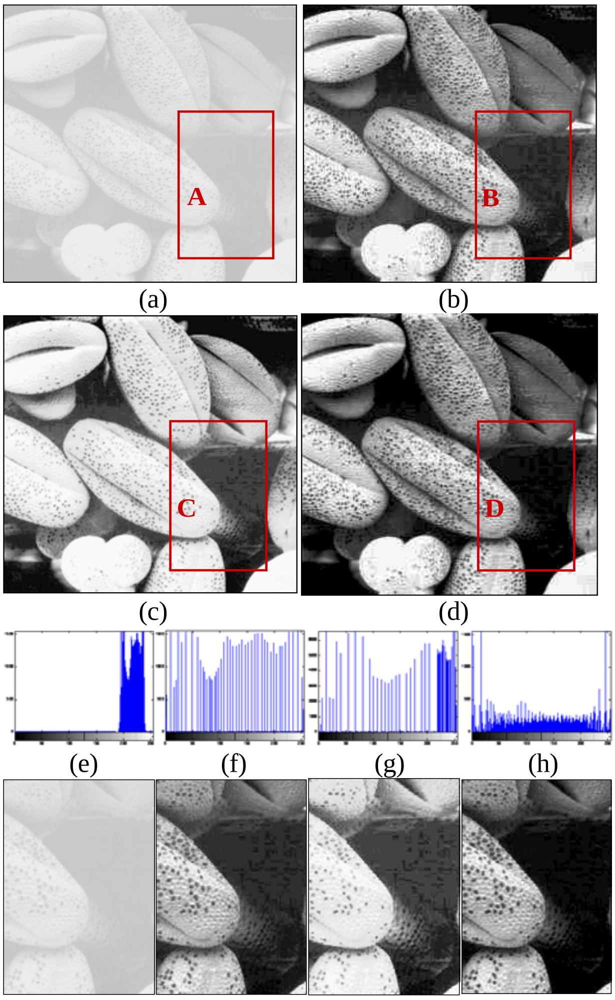

Figure 4 – Comparison of the CE images. (a) low-contrast input image (500×500 test image 1, 8-bit depth), (b) HE image, (c) SMQT CE image, (d) proposed CE image, (e) histogram of (a), (f) histogram of (b), (g) histogram of (c), (h) histogram of (d), (i) enlarged region A of (a), (j) enlarged region B of (b), (k) enlarged region C of (c) , (l) enlarged region D of (d).

algorithm is flatter. Also the actual number of grey levels used in representing the enhanced image is increased by ED.

This fact shows that the proposed CE algorithm is an effective algorithm that modifies the dynamic range as well as the contrast. Figures 4(i), 4(j), 4(k), and 4(l) show the enlarged regions A, B, C, and D indicated in Figures 4(a), 4(b), 4(c), and 4(d), respectively. After HE and SMQT, the artefacts become noticeable in the background (dark region) in Figure 4(j) and 4(k). In Figure 4(l) of the proposed algorithm, the background is dark, and the texture of the object becomes more vivid.

Figure 5 shows the comparison of the resultant images and histograms enhanced by the HE, SMQT and proposed CE methods. Figure 5(a) shows the low-contrast test image 2 (500×400, 8-bit depth), whose grey level is mainly distributed in a limited range of middle grey levels. Figures 5(b) 5(c), and 5(d) show the images enhanced by the HE, SMQT, and proposed CE methods, respectively. Figures 5(e), 5(f),

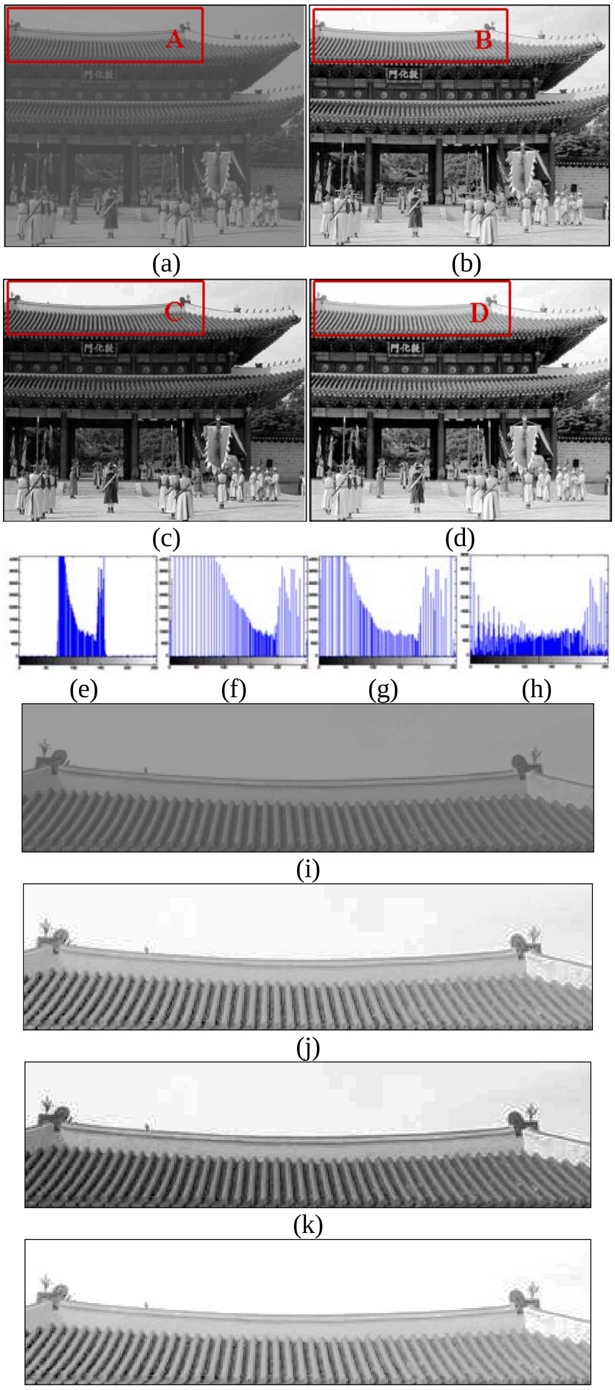

Figure 5 – Comparison of the CE images. (a) low-contrast input image (500×400 test image 2, 8-bit depth), (b) HE image, (c) SMQT CE image, (d) proposed CE image, (e) histogram of (a), (f) histogram of (b), (g) histogram of (c), (h) histogram of (d), (i) enlarged region A of (a), (j) enlarged region B of (b), (k) enlarged region C of (c) , (l) enlarged region D of (d).

5(g), and 5(h) illustrate the histograms of Figures 5(a), 5(b), 5(c), and 5(d), respectively. Figure 5(i) shows the enlarged region A indicated in Figure 5(a). Figures 5(j), 5(k), and 5(l) illustrate the enlarged regions B, C and D indicated in Figures 5(b), 5(c), and 5(d), respectively. The block artefacts in the sky and the ringing artefacts around the roof in Figure

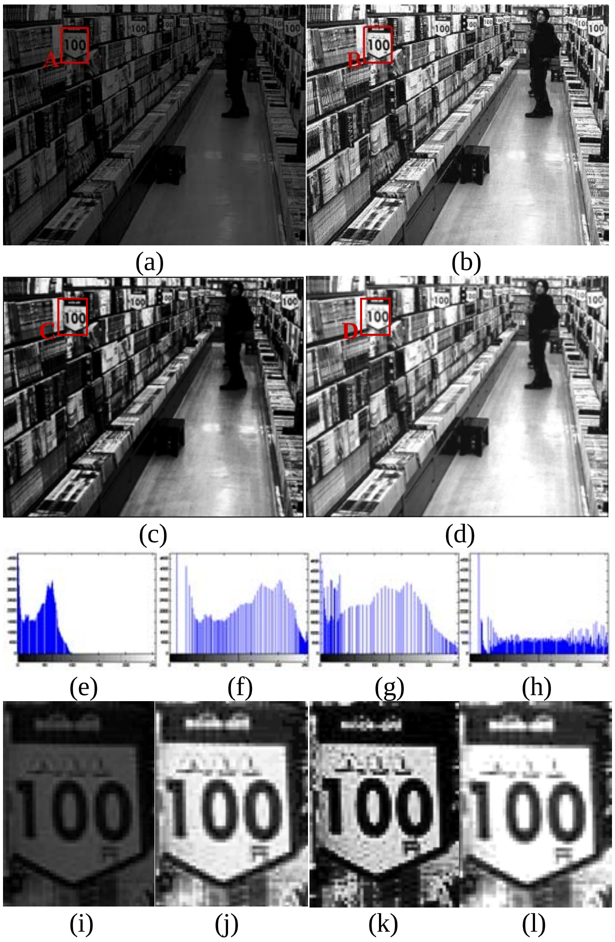

Figure 6 – Comparison of the CE images. (a) low-contrast input image (500×400 test image 3, 8-bit depth), (b) HE image, (c) SMQT CE image, (d) proposed CE image, (e) histogram of (a), (f) histogram of (b), (g) histogram of (c), (h) histogram of (d), (i) enlarged region A of (a), (j) enlarged region B of (b), (k) enlarged region C of (c) , (l) enlarged region D of (d).

5(j) and 5(k) do not originally exist in the low-contrast input image (Figure 5(i)). After HE (Figure 5(j)) and SMQT (Figure 5(k)), they become noticeable whereas they are properly removed in the image enhanced by the proposed CE algorithm (Figure 5(l)). The simulation result shows the effectiveness of the proposed CE algorithm, where natural gradation in the smooth region is noticed because the modified ED algorithm of the proposed method increases the number of grey levels.

Figure 6 shows the simulation result for test image 3 (500×400). Figure 6(a) shows the low-contrast input image with 8-bit depth. Figures 6(b), 6(c), and 6(d) illustrate the images enhanced by the HE, SMQT, and proposed CE methods, respectively. Figures 6(e) shows the histogram of Figure 6(a) which is mainly distributed in a limited range of low grey levels. Figures 6(f), 6(g), and 6(h) show the histograms of Figures 6(b), 6(c) and 6(d), respectively. The histogram of the proposed CE algorithm is flatter than that of the HE and SMQT methods. Figures 6(i), 6(j), 6(k), and 6(l) illustrate the enlarged regions A, B, C, and D indicated in Figures 6(a), 6(b), 6(c), and 6(d), respectively. The artefacts near the number plate are reduced by the proposed CE algorithm.

In summary, the proposed CE algorithm is effective to enhance the low-contrast image such as Figures 4(a), 5(a), and 6(a), which have a narrow distribution range in the histogram.

5. CONCLUSIONS

This paper proposes a CE algorithm combined with modified ED. The proposed CE algorithm consists of the HE and modified ED. The modified ED algorithm reduces the block artefacts, such as the false contours in the smooth region, and ringing artefacts around edges of the enhanced image. Therefore, the proposed CE algorithm gives better results than the HE method and SMQT method, effectively enhancing the low-contrast image with the number of grey levels increased by the ED. Experimental results with a number of test images show that the proposed CE algorithm efficiently enhances the contrast of the low-contrast image. It can be used as a post-processing for CE with simultaneous artefact reduction in various display devices.

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