Reversible Data Hiding With Brightness Preserving Contrast Enhancement by Two-Dimensional Histogram Modification

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***Abstract*— Recently, contrast enhancement with reversible data hiding (CE-RDH) has been proposed for digital images to hide useful data into contrast-enhanced images. In existing schemes, one-dimensional (1D) or two-dimensional (2D) histogram is equalized during the process of CE-RDH so that an original image can be exactly recovered from its contrast-enhanced version. However, noticeable brightness change and color distortion may be introduced by applying these schemes, especially in the case of over enhancement. To preserve image quality, this paper presents a new 2D histogram based CE-RDH scheme by taking brightness preservation (BP) into account. In particular, the row or column of histogram bins with the maximum total height are chosen to be expanded at each time of histogram modification, while the row or column of bins to be expanded next are adaptively chosen according to the change of image brightness. Experimental results on three color image sets demonstrate efficacy and reversibility of the proposed scheme. Compared with the schemes using 1D histogram, image brightness can be preserved more finely by modifying the generated 2D histogram. Moreover, our proposed scheme preserves image color and brightness while achieving better image quality than the existing schemes.**

***Index Terms*— Reversible data hiding, image enhancement, 2D histogram, brightness preservation, histogram equalization.**

I. Introduction

CONTRAST enhancement (CE) is a useful technique to improve the visibility of image or video details. It has been an active research topic for decades and widely used in industrial and medical image processing (e.g., [1]–[3]). The CE procedure is usually performed on images with low dynamic range to bring out the regions of interest (ROI). In the literature, a number of image CE methods have been proposed to improve the visual effect, such as in [4]–[7]. Among these methods, histogram equalization (HE) is a basic technique (e.g., [8]–[10]) to reveal the unclear details in image or video content.

As image CE may be performed to improve visibility of unclear details, more or less information loss may be caused if the changes are permanent. For instance, there may be multiple ROIs in one image, but it is hard to properly enhance all ROI regions at the same time. Due to the limitation of storage space or bandwidth for transmission, the original image is not always at hand, which is required to generate a new contrast-enhanced image. Therefore, it is desirable to achieve the reversible CE so that an original image can be exactly recovered from its contrast-enhanced versions if needed. Recently, a number of methods have been proposed to fulfill this requirement, such as in [11]–[28].

Generally speaking, reversible image CE is highly related to the technique of reversible data hiding (RDH). With the RDH (e.g., [29]–[44]), a piece of information can be hidden into a cover image so that the original image can be exactly recovered after extracting the hidden data. An intuitive way to accomplish reversible image CE is to hide the recovery information (e.g., the difference between the original and contrast-enhanced images) with RDH, but embedding additional data into the contrast-enhanced image may introduce additional distortions. A more skillful way is to perform HE with RDH so that the CE effect can be achieved simultaneously with data embedding. That means an original image can be recovered from the contrast-enhanced image just like with the RDH methods. In addition, extra data can be hidden in contrast-enhanced images, which may be extracted to enable additional functionalities such as authentication and content annotation.

To our best knowledge, the first attempt to achieve the HE through RDH was made in [11], where the highest two bins in the image histogram are chosen to be equalized at each time. By equalizing each of the chosen bins to two adjacent bins and repeating the histogram modification, the HE effect can be obtained with data embedding. To avoid the overflow of pixel values due to histogram modification, the

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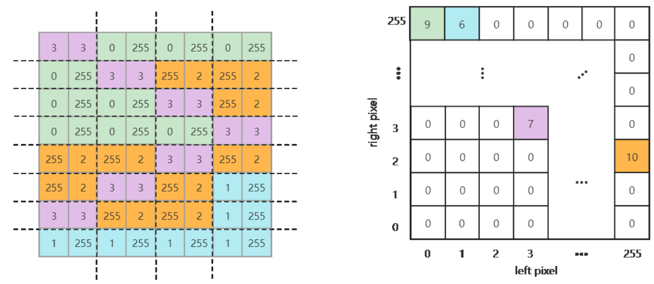
boundary pixel values are modified before data embedding, but visual distortions may be caused in the preprocessing. In [12], an improved RDH method is proposed by setting the upper bound of the relative contrast error defined in [45]. In [13], a reversible CE method is proposed for medical images by adaptively choosing the interval containing the minimum number of pixels on each side of the histogram. By identifying the principal pixel values in the segmented background, the region of interest (ROI) can be exclusively enhanced. In [15], image contrast is improved by making the histogram shifting process adaptive to the distribution characteristics. Another RDH algorithm is proposed for medical images in [16] to enhance the contrast in texture area, and a ROI-based scheme with CE is proposed in [19]. In [18], an RDH algorithm is proposed to achieve contrast enhancement of the ROI and tamper localization for medical images, while an automatic CE scheme is further proposed in [27]. Nevertheless, the disorder of pixel values in preprocessing cannot be completely avoided so that artificial distortions may still be generated. To address this issue, an improved preprocessing was proposed in [20] to alleviate such distortions by preserving the order of pixel values. A bookkeeping is generated to record the changes made in preprocessing, which is to be hidden into the enhanced image during histogram modification. To improve the performance in terms of the peaked signal-to-noise ratio (PSNR) and CE effect, two-dimensional (2D) histogram is modified in [21] to perform RDH with image CE. To prevent the overflow of pixel values, a new preprocessing is proposed to shrink a 2D histogram to vacate its boundary. After that, the rows and columns of histogram bins containing the maximum number of pixel pairs are expanded in four directions, respectively. To improve local contrast and embedding capacity, Jafar *et al.* [17] formulated the calculation of the Laplacian to achieve reversibility. To solve the noise amplification issue in [17], a multiple histogram modification based method was proposed in [28], which classifies pixels with subtly-designed features and utilizes an adaptive embedding strategy based on the classification results.

Besides the aforementioned schemes, a novel automatic CE method has been proposed in [14] without the need of preprocessing. Specifically, the highest bin in one dimensional (1D) histogram is chosen to be expanded while the lowest bin is merged with one adjacent bin. As no overflow occurs in this process, a concurrent location map needs to be generated to record the pixels contained in the merged bins. The histogram can be iteratively modified until the ever-increasing location map cannot be accommodated by equalizing the highest bin for data embedding in the next step. However, over enhancement effect may occur with the automatic CE method in [14], which makes the enhanced image look unnatural. As the brightness preservation (BP) methods have been studied to reduce the excessive increase of contrast (e.g., [46], [47]), a reversible CE method with BP is proposed in [22]. By adaptively choosing the bins to be equalized according to the original image brightness, the method preserves the image brightness to an acceptable level so that the enhanced image looks more like to the original one. As the better CE effect can be obtained with 2D histogram (e.g., [4], [7], [21]), how to perform the BP-based reversible CE with 2D histogram has not been explored.



(a) An 8×8 image partitioned into 32 pixel pairs. (b) A 2D histogram of the 8×8 image.

Fig. 1. Generation of a 2D histogram from an image with size of 8 × 8.

In this paper, we propose a new BP-based reversible CE scheme to avoid the over enhancement that may be caused by applying the methods in [11], [14] and [21]. Different from the method in [22], a 2D histogram is used in the proposed scheme to enable the fine adjustment of image brightness. In particular, the row or column of histogram bins containing the maximum number of pixel value pairs are adaptively chosen to be equalized at each time. The corresponding row or column of bins containing the least pixel pairs are chosen to be merged with the adjacent one, while a concurrent location map is generated to record the changes. To preserve image brightness, histogram modification in the next step can be determined according to the brightness difference until a stopping condition is met. That is, we combine the advantages of the methods proposed in [21] and [22] to improve the performance of reversible image CE with BP. The proposed scheme has been applied on three sets of test images. Experimental results demonstrated its efficiency and reversibility. Compared with the methods in [14], [22] and [25], the image brightness can be better preserved while image quality can be improved by using our scheme. Our contribution can be summarized as follows.

- BP based CE-RDH is performed by modifying a 2D histogram to improve quality of enhanced images.
- The proposed scheme achieves granular preservation of image brightness and color. And experimental results show that better performance than the existing CE-RDH schemes in [14], [22] and [25] can be achieved.

The rest of this paper is organized as follows. Section II presents the preliminary for RDH based on 2D histogram modification by giving an overview of the related work. Then a new reversible CE scheme is proposed in Section III. In Section IV, the experimental results on color images are given and the performance is evaluated and compared with the schemes in [14], [22] and [25]. Finally, we conclude the paper in Section V.

II. Preliminary and Related Work

In this section, we first introduce the procedure of 2D histogram generation. Then the preliminary for RDH based on multi-dimensional histogram modification is presented, and the related work on RDH with image CE is reviewed.

A. 2D Histogram Generation

For a grayscale image, a 1D histogram is generated by counting the occurrences of every possible gray value (e.g., integers within [0, 255] for an 8-bit pixel value). To calculate a 2D histogram, a pixel and its adjacent right pixel are combined to form a pixel pair, and then the non-overlapping pixel pairs can be scanned one by one as shown in Fig. 1. In this example, an 8×8 image is given on the left, which is partitioned into 32 pixel pairs by dotted lines. For easy identification, pixel pairs with the same left and right values are painted in the same color. It can be seen that there are 7 purple pixel pairs, 9 green pixel pairs, 10 orange pixel pairs and 6 blue pixel pairs. Since a pixel value ranges from 0 to 255, a 2D histogram $H = \{h(0,0), h(0,1), \ldots, h(255,255)\}$ is generated by counting the number of every possible pixel pair as shown in Fig. 1(b). In the 2D histogram, $h(i, j)$ represents the number of pixel pairs with the same values in the image (i.e., the left pixel value is i for $i \in \{0, 1, \ldots, 255\}$ and the right pixel value is j for $j \in \{0, 1, \ldots, 255\}$).

In such a 2D histogram, the bins in the same column have the same left pixel value i, while the bins in the same row have the same right pixel value j. For a pixel with value k, it can be the left or the right one in a pixel pair. So a bin with value k in 1D histogram is equivalent to the combination of one column of bins with $i = k$ and one row of bins with $j = k$ in the 2D plane. Within 2D histogram, the column of bins with $i = k$ and the row of bins with $j = k$ are unnecessary to be modified together but can be separately processed.

A 2D histogram can be generated not only from pixel values, but also from prediction errors between original and predicted pixel values. In [30] and [31], the correlations between prediction-errors are utilized for RDH, so that every two adjacent prediction-errors are joint and a 2D prediction-error histogram is generated, respectively. Compared with equalizing a 1D histogram, the adjustment of image brightness can be controlled more finely by modifying a 2D histogram. So, we focus on 2D histogram modification based image CE with RDH in this paper.

B. RDH Based on Multi-Dimensional Histogram Modification

Different from conventional RDH schemes based histogram modification, the schemes based on multi-dimensional histogram modification (e.g., [21], [30]–[32], [41]–[43]) and multiple histograms modification (e.g., [28], [35]–[40]) can exploit more redundancy in image content for data embedding.

RDH based on 2D histogram modification has been proposed in [30] and [31]. The method proposed in [30] considers every two adjacent prediction-errors so that more image redundancy can be exploited by utilizing the correlations within them. Data embedding is achieved by expanding and shifting the 2D prediction errors histogram (PEH). Differently, the technique of difference-pair-mapping is developed in [31] for RDH by generating and expanding a 2D difference-histogram for data embedding. In [41], multiple histograms modification is combined with 2D PEH modification. As 2D histogram equalization has been adopted in [4] and [10] for image CE,

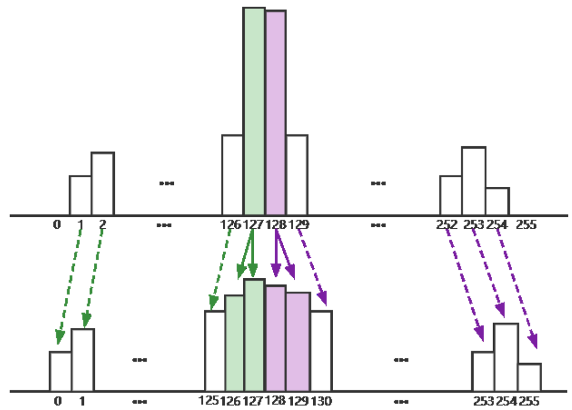


Fig. 2. An illustration of one-dimensional histogram modification in [20].

an RDH method with CE was proposed in [21] based on 2D histogram modification and an adaptive RDH scheme with CE based on multiple histogram modification was proposed in [28]. To further exploit image redundancy, RDH methods based on 3D prediction error expansion were proposed in [42] and [43], respectively. As high computational complexity is introduced by using a 3D histogram, double deep Q-networks are adopted to guide the modification directions in [42].

C. Related Work

Most of existing CE-RDH schemes enhance images by histogram equalization. According to the type of histogram, these CE-RDH schemes can be classified into two categories: (1) methods based on PEH (e.g., [17], [28]) and (2) methods based on pixel values histogram (PVH) (e.g., [14], [20]–[25]). Both kinds of methods embed data by histogram modification. Specifically, the type of methods based on PEH focus on improving embedding capacity and image local contrast by modifying the histogram of prediction errors, while the other type of methods embed data by directly modifying the histogram of pixel values.

According to whether the iteration time (i.e., time of histogram modification) is manually set, the CE-RDH schemes can be divided into two categories: (1) methods using preset iteration time (e.g., [20], [21], [25]), and (2) automatic CE-RDH scheme [14], [22]. Since enhancement effect is positively correlated with iteration time, images may be over-enhanced or under-enhanced when the iteration time is improperly set. In the second category, a stopping condition is predefined so that automatic CE-RDH can be performed without manually choosing the iteration time. Hence, it is critical to choose the appropriate iteration time in both categories of CE-RDH schemes to achieve satisfactory enhancement effect.

In [20] and [21], the iteration time needs to be preset, which is represented by S. Histogram shifting is performed for S times and side information required for image recovery is embedded into the histogram. To make room for the S-time histogram shifting, histogram shrinkage is performed in preprocessing. Specifically, the histogram is divided into two fragments according to whether the pixel value is larger than 127 or less than 128. In each fragment, the highest bin is selected to be expanded for data embedding, and bins closer

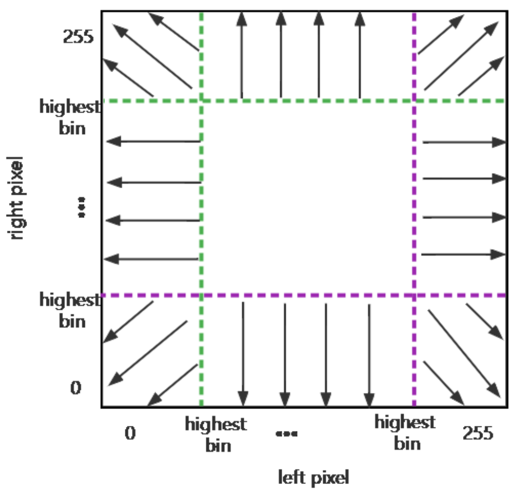


Fig. 3. An illustration of two-dimensional histogram modification in [21].

to the boundary are shifted to the boundary as shown in Fig. 2, where bin 127 and bin 128 are highest in the left and right fragments for illustration. Similarly, 2D histogram modification is performed in [21] as illustrated in Fig. 3. At each iteration of histogram modification, the combination of two rows and two columns containing the maximum number of pixel pairs are chosen at the same time. The chosen rows and columns are expanded while the outer rows and columns are shifted toward the boundary of 2D histogram. As the schemes in [20] was initially proposed for grayscale images,, the HSV color model is adopted in[25] to extend it to color images. Specifically, the V component (i.e., the maximum value of red, green and blue components in every RGB pixel) is enhanced while the other components are modified accordingly.

Since BP is not considered in the scheme proposed in [14], image brightness will be increased if the histogram bins are shifted to the right. On the contrary, image brightness will be decreased if the histogram bins are shifted to the left. As a result, the enhanced image may get darker or brighter if the direction of histogram shifting is biased during the enhancement process. To address this issue, the average brightness of all pixels is calculated at each iteration of histogram modification and compared with the initial average brightness of the original image in [22]. Specifically, the difference in average brightness is calculated by using Eq. (1), where w and h represent width and height of the image, $p_{i,j}$ represents value of the pixel in the i^{th} row and j^{th} column of the original image, and $p'_{i,j}$ represents value of the pixel in the i^{th} row and j^{th} column of the enhanced image.

$$diff = \frac{\sum_{i=0}^{w}\sum_{j=0}^{h} p'_{i,j}}{w \times h} - \frac{\sum_{i=0}^{w}\sum_{j=0}^{h} p_{i,j}}{w \times h} \tag{1}$$

If $diff > 0$, the histogram bins should be shifted to the left. Otherwise, the histogram bins should be shifted to the right. In this way, a relatively higher bin and a relatively lower bin are adaptively chosen according to the change of brightness so that image brightness is preserved after histogram modification.

III. Proposed Reversible Contrast Enhancement Scheme

In this section, a new scheme for reversible CE is presented. Fig. 4 shows the whole procedure of our proposed scheme, in which histogram equalization is achieved by iteratively modifying a 2D histogram of the original image. To avoid over enhancement, BP is taken into consideration in bin merging and histogram shifting. At each iteration, direction of histogram shifting and embedded position are adaptively chosen according to the change in image brightness until the maximum embedding capacity is reached. To ensure that the original image can be recovered when needed, the equalization information at each iteration and other side information is kept and embedded to the enhanced image. At last, the equalization information is embedded to specified positions of the enhanced image so as to be correctly extracted. To extend the proposed scheme to color images, the procedure for grayscale image is applied to R, G and B channels, respectively.

In the following, the scheme proposed for grayscale images is presented in details, including: (1) 2D histogram equalization, (2) brightness preservation, (3) generation of side information, (4) embedding capacity calculation and control, and (5) data extraction and image recovery.

A. 2D Histogram Equalization

At each iteration, the row or column of histogram bins in a 2D plane containing the maximum number of pixel pairs are chosen to be modified. Meanwhile, the corresponding row or column of histogram bins containing the minimum number of pixel pairs are chosen to be merged with its adjacent row or column to vacate space for histogram shifting. Depending on the value of the chosen row or column, histogram modification can be performed in four directions, as shown in Fig. 5 and Fig. 6, respectively.

Without loss of generality, let p be the left pixel value of the column of bins containing the maximum number of pixel pairs and let r be the one containing the minimum number of pixel pairs. In left histogram shifting (LHS) and right histogram shifting (RHS), column r is merged with column $r+d_h$, where d_h is defined by

$$d_h = \begin{cases} -1, & \text{if } p < r \text{ (RHS)} \\ 1, & \text{if } p > r \text{ (LHS).} \end{cases} \tag{2}$$

Then for a pixel pair with value (i, j), its value is modified to (i', j) to expand column p in LHS by

$$i' = \begin{cases} i, & \text{if } i \le r \text{ or } i > p \\ i-1, & \text{if } r < i < p \\ i-b_e, & \text{if } i = p. \end{cases} \tag{3}$$

where b_e is a bit value (0 or 1) to be embedded if $i = p$. In RHS, i, j is modified to (i', j) by

$$i' = \begin{cases} i, & \text{if } i < p \text{ or } i \ge r \\ i+1, & \text{if } p < i < r \\ i+b_e, & \text{if } i = p. \end{cases} \tag{4}$$

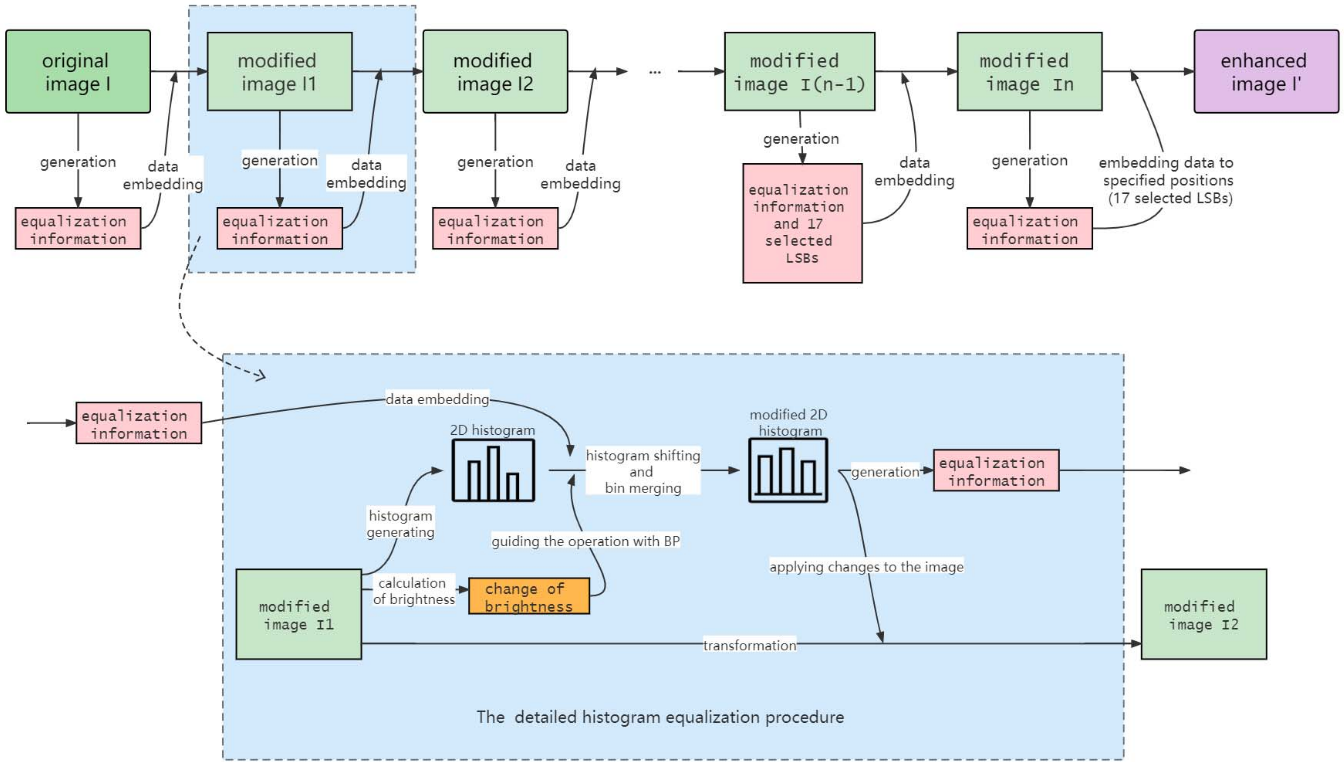
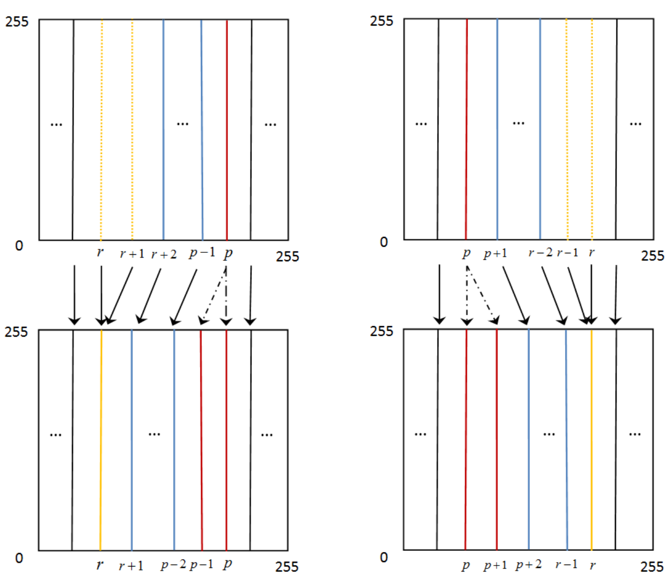
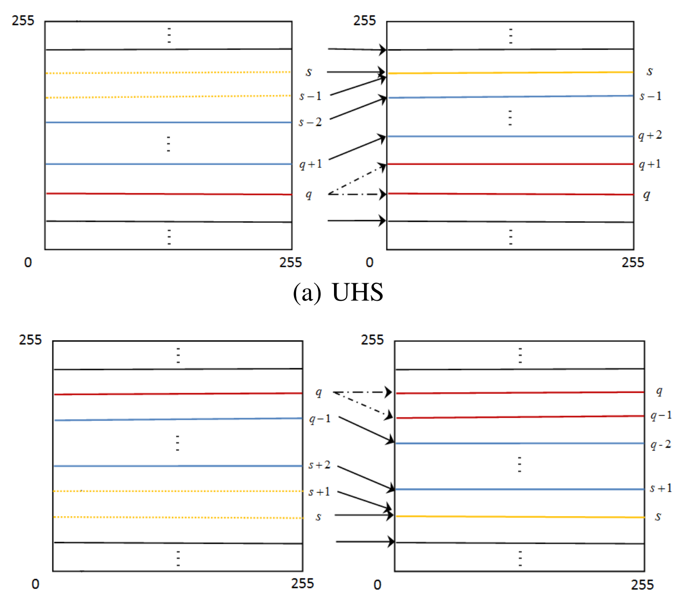


Fig. 4. Flowchart of image enhancement by iteratively equalizing 2D histogram and preserving brightness, the operations performed at each iteration of histogram modification are shown in the enlarged blue box. The iteration time of histogram modification is denoted by n, which depends on embedding capacity of an image.



(a) LHS (b) RHS

Fig. 5. 2D histogram modification in the horizontal directions, denoted by LHS (left) and RHS (right).



(a) UHS

(b) DHS

Fig. 6. 2D histogram modification in the vertical directions, denoted by UHS (up) and DHS (down).

Similarly, let q be the right pixel value of the row of bins containing the maximum number of pixel pairs and let s be the one containing the minimum number of pixel pairs. In down histogram shifting (DHS) and up histogram shifting (UHS), row s is merged with row $r + d_v$, where d_v is defined by

$$d_v = \begin{cases} -1, & \text{if } q < s \text{ (UHS)} \\ 1, & \text{if } q > s \text{ (DHS)}. \end{cases} \quad (5)$$

Then in DHS, each pixel pair i, j is modified to (i', j) by

$$j' = \begin{cases} j, & \text{if } j \le s \text{ or } j > q \\ j-1, & \text{if } s < j < q \\ j - b_e, & \text{if } j = q, \end{cases} \tag{6}$$

where b_e is a bit value (0 or 1) to be embedded if $i = p$. And in UHS, (i, j) is modified to (i, j') by

$$j' = \begin{cases} j, & \text{if } j < q \text{ or } j \ge s \\ j+1, & \text{if } q < j < s \\ j + b_e, & \text{if } j = q, \end{cases} \tag{7}$$

In the above operations, the value of p is limited to a certain range rather than arbitrarily chosen. It is required that $p > 1$ in LHS and $p < 254$ in RHS to make room for merging and shifting. Similarly, it is required that $q > 1$ in DHS and $q < 254$ in UHS. The range of r is determined by shifting direction and the value of p. In LHS, r should be within the range $[0, p-1)$, and in RHS, it should be within the range $(p+1, 255]$. Similarly, s should be within the range $[0, q-1)$ in DHS, and it should be within $(q+1, 255]$ in UHS.

By modifying the 2D histogram, fine adjustment of image brightness can be conducted because only the left or right pixel value in the same pair is changed at each repetition. After that, the row or column of histogram bins containing the maximum number of pixel pairs are found out from the modified histogram so that values of p and r, or those of q and s, need to be updated. 2D histogram modification as illustrated in Fig. 5 and Fig. 6 may be iteratively repeated until a stopping condition is satisfied, which is to be introduced as in Section III-D.

B. Brightness Preservation

To preserve image brightness, the 2D histogram can be modified in a pendular way, which is similar to the 1D case in [22]. The difference is brightness of left pixels and brightness of right pixels are separately calculated. The average brightness of all left pixels is denoted by $brightness_L$, while the average brightness of all right pixels is denoted by $brightness_R$. As the pixel values are subtracted by one or unchanged in LHS, $brightness_L$ is decreased by the histogram modification. On the contrary, $brightness_R$ is increased by the histogram modification in RHS. Similarly, $brightness_R$ is decreased in the case of DHS and be increased in the case of UHS.

At each time of histogram modification, both $brightness_L$ and $brightness_R$ are compared with the original ones without any modification to determine histogram modification at the next iteration. When $brightness_L$ exceeds the original one, histogram modification in LHS is chosen for the next iteration. Otherwise, histogram modification in RHS may be performed at the next iteration. Meanwhile, if $brightness_R$ exceeds the original one, histogram modification in DHS may be chosen while histogram modification in UHS may be performed when $brightness_R$ is less than the original one. If $brightness_L$ is identical to the original one, the same strategy as in the first time of histogram modification is adopted. That is, the one providing more embedding capacity between LHS and RHS is selected to be a candidate. Likewise, if $brightness_R$ is identical to the original one, the choice with more embedding capacity is chosen. As for which of $brightness_L$ and $brightness_R$ is chosen to be preserved at the next iteration, the one providing higher embedding capacity is always chosen.

C. Generation of Side Information

To recover the original image, p (or q), the corresponding value of r (or s) and shifting direction (vertical or horizontal) of each time of histogram modification should be provided. At each iteration, 8 bits are allocated respectively for p (or q) and r (or s) and 1 bit is allocated for direction of histogram modification (e.g., 0 for horizontal and 1 for vertical). Besides the 17-bit equalization information, pixel pairs merged in any case of LHS, RHS, UHS or DHS need to be recorded. For instance, in the case of LHS, the column containing the minimum pixel pairs is r, while the adjacent column to be merged is $r+1$. Before merging column r with column $r+1$, all pixel pairs are scanned in order and all left pixels with value r or $r+1$ are marked by 0 or 1, respectively. All these marks make up a location map for merged pixels pairs at each iteration, which is concatenated with the 17-bit equalization information of the previous iteration and embedded by expanding the column of histogram bins with value p. At last iteration, the side information to be embedded is slightly different. Since there is no next iteration to embed current 17-bit equalization information, the LSBs of 17 pixels of which positions are randomly selected with a secret key, are replaced with the equalization information. So the original 17 LSB values also need to be embedded to the bins with value p while the pixel pairs containing the 17 selected pixels are excluded from calculating the 2D histogram and the following modification.

D. Embedding Capacity Calculation and Control

According to the discussion in Section III-C, at least 34 bits should be allocated for the data to be embedded at the last iteration, which contain 17 bits for the selected 17 LSBs and 17 bits for equalization information of the previous iteration. So the pure capacity in data embedding (i.e., total embedding bits minus those bits in the current location map) is used as the stopping criterion. The iteration of histogram modification is continued only when the embedding capacity exceeds 34 bits. Otherwise, the iteration should be terminated and returned to the previous state. More precisely, the image is restored to the version before histogram equalization at the previous iteration so that the operations at the last iteration can be performed as discussed. That is, 17 pixels are randomly selected for saving of equalization information at the last iteration. It is worth mentioning that the pixel pairs containing the 17 selected pixels are excluded from calculating the 2D histogram and the following histogram modification. After the last iteration, LSBs of the 17 selected pixels are replaced with the last equalization information.

E. Data Extraction and Image Recovery

In the following, we introduce how to extract the hidden data from the enhanced image and recover the original image.

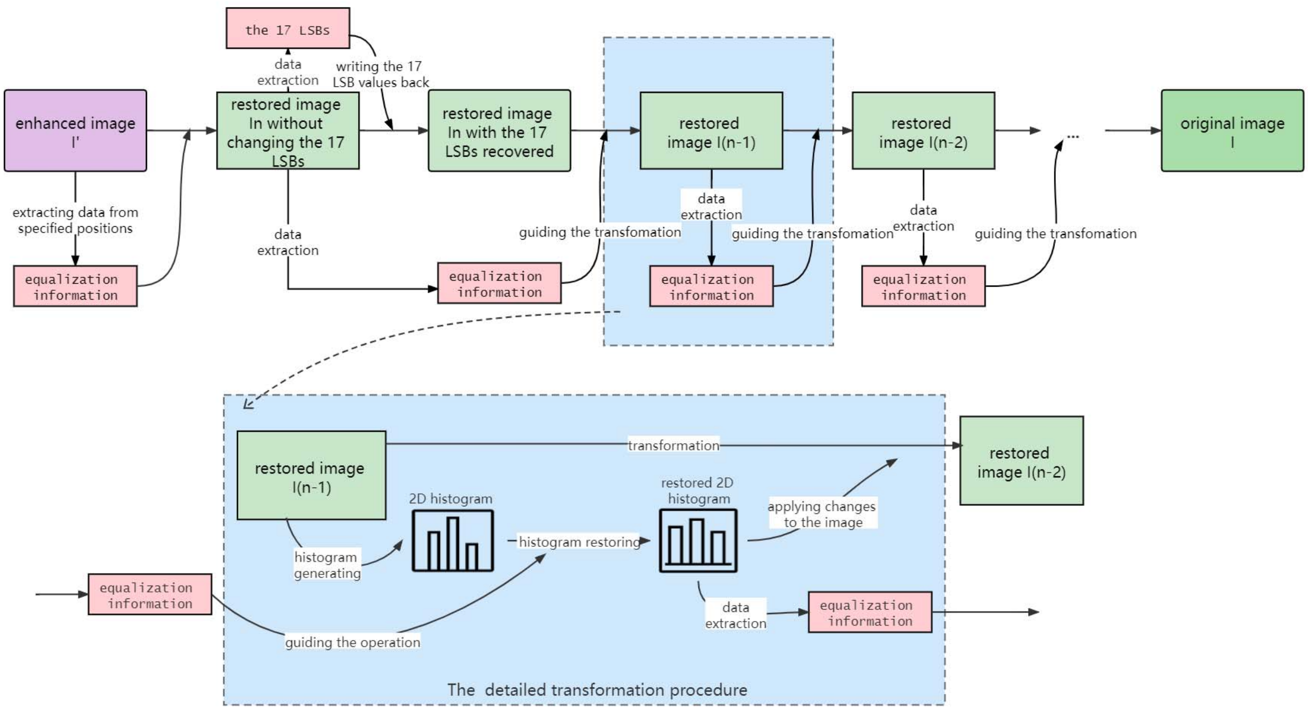


Fig. 7. Flowchart of image recovery by iteratively extracting equalization information and restoring modified pixels, and the operations at each iteration of histogram modification are shown in the enlarged blow box.

For grayscale images, from the LSBs of the 17 chosen pixels, a pair of row or column values are retrieved and the direction of histogram shifting (horizontal or vertical) can be known. By comparing the relation between the two values, the mode (i.e., LHS, RHS, UHS or DHS) of the last histogram modification can be further inferred. A 2D histogram is calculated without counting the pixel pairs containing the 17 pixels. If the histogram modification is horizontal, the bit values embedded in LHS or RHS can be extracted with the retrieved p by

$$b_e' = \begin{cases} 0, & \text{if } i = p \\ 1, & \text{if } i = p - d_h, \end{cases} \tag{8}$$

where b_e' is a bit value extracted from a pixel pair with left value $i = p$ or $i = p - d_h$, and d_h equals to 1 for LHS and -1 for RHS. Similarly, the bit values embedded in UHS or DHS can be extracted with the retrieved q by

$$b_e' = \begin{cases} 0, & \text{if } j = q \\ 1, & \text{if } j = q - d_v, \end{cases} \tag{9}$$

where b_e' is a bit value extracted from a pixel pair with right value $j = q$ or $j = q - d_v$, and d_v equals to 1 for DHS and -1 for UHS. With the extracted bit values, which include the merging information, a pixel pair (i', j) modified by RHS can be restored to (i, j) by

$$i = \begin{cases} i', & \text{if } i' < p + 1 \text{ or } i' > r \\ i' - b_l', & \text{if } i' = r \\ i' - 1, & \text{if } p < i' < r \ , \end{cases} \tag{10}$$

where b_l' is the bit value in extracted merging information that corresponds to the pixel pair (i', j). Similarly, a pixel pair (i', j) modified by LHS can be restored to (i, j) by

$$i = \begin{cases} i', & \text{if } i' < r \text{ or } i' > p - 1 \\ i' + b_r', & \text{if } i' = r \\ i' + 1, & \text{if } r < i' < p \ , \end{cases} \tag{11}$$

where b_r' is the bit value in extracted merging information that corresponds to the pixel pair (i', j). For UHS, a pixel pair (i, j') can be restored to (i, j) by

$$j = \begin{cases} j', & \text{if } j' < q + 1 \text{ or } j' > s \\ j' - b_u', & \text{if } j' = s \\ j' - 1, & \text{if } q < j' < s, \end{cases} \tag{12}$$

where b_u' is the bit value in extracted merging information that corresponds to the pixel pair (i, j'). Similarly, a pixel pair (i, j') modified by DHS can be restored to (i, j) by

$$j = \begin{cases} j', & \text{if } j' < s \text{ or } j' > q_1 \\ j' + b_d', & \text{if } j' = s \\ j' + 1, & \text{if } s < j' < q, \end{cases} \tag{13}$$

where b_d' is the bit value in extracted merging information that corresponds to the pixel pair (i, j'). In addition to the merging information, the previous equalization information and the original LSB values of the 17 pixels are also obtained. After writing the extracted LSB values back, a new 2D histogram is calculated including all pixel pairs in the image so that data extraction and histogram restoration can be iteratively performed until the previous equalization information (p and r, or q and s) consists of only zeros. The procedure of data extraction and original image recovery is summarized in Fig. 7. Similar to [22], image recovery in the case of color images consists of three parts by applying the above procedure on R, G and B channels, respectively.

IV. Experimental Results

In the experiments, the proposed scheme was compared with three existing reversible CE schemes proposed in [14], [22] and [25]. All of these schemes were applied on three sets of test images, respectively. The first image set includes eight test images with the size of 512 × 512, which were downloaded from USC-SIPI.[1] The second image set consists of twenty-four test images with the size of 768 × 512, which were downloaded from Kodak Lossless True Color Image Suite.[2] The third image set includes eighteen color images with the size of 500 × 500, which were downloaded from McMaster dataset[3] [48]. It should be noted that the contrast of images in McMaster dataset was reduced before being enhanced by

$$\begin{cases} p'_{i,j} = I_{avg} + \alpha \times (p_{i,j} - I_{avg}) \\ I_{avg} = \frac{\sum_{i=0}^{w}\sum_{j=0}^{h} p_{i,j}}{w \times h}, \end{cases} \quad (14)$$

in which $p_{i,j}$ and $p'_{i,j}$ respectively represent the original pixel value and the one after contrast reduction, I_{avg} represents the average brightness of an image, while w and h represent the image width and image height, respectively. In Eq. (14), α is a factor used to reduce the contrast, which was set to 0.7 in our experiments so that every pixel value $p'_{i,j}$ in R, G and B channels was rounded to the nearest integer within $[0, 255]$. The images obtained after contrast reduction had the same average brightness as the original ones in McMaster dataset, which were used as test images in our experiments.

The automatic CE scheme in [14], hereinafter referred to as ACERDH, was directly applied to R, G and B channels, respectively. The scheme in [25] was included in the comparison because it was developed for color images, which is denoted by Guan's. The scheme in [22], which is denoted by Kim's, was also included in performance comparison so that the advantages of modifying 2D histogram in the proposed scheme can be revealed. In addition to the side information to be used for image recovery, extra bit values were also hidden into each contrast-enhanced image, which were randomly generated so that the number of zeros was close to that of ones.

In the following, the performance of these schemes will be evaluated and compared from eight perspectives, i.e., visual effect, contrast enhancement, image quality, brightness preservation, color preservation, embedding rate, security and computational complexity analysis.

A. Visual Effect

In applying the proposed scheme, the time of histogram modification (i.e., applying the LHS, RHS, UHS or DHS) is denoted by n. Fig. 8 shows the enhancement effect after applying the four schemes on the same test images. For convenience of comparison, the same time of histogram modification was set for all of the four schemes compared, but there are some differences in parameter setting. In [14], [22] and [25], the highest bin in 1D histogram is chosen at each time, which is equivalent to one row and one column of bins in 2D histogram. With the proposed scheme, only a row or a column of bins are selected in the 2D plane at each iteration, so that the time of histogram modification is set to $\frac{n}{2}$ when applying schemes in [14], [22] and [25].

From the results as shown in Fig. 8, it can be seen that the proposed scheme and the scheme in [22] preserve global brightness and image color, while applying the other two schemes [14], [25] may affect image quality or color. Specifically, applying the ACERDH may result in color distortion, while applying the Guan's scheme may bring unexpected artifacts.

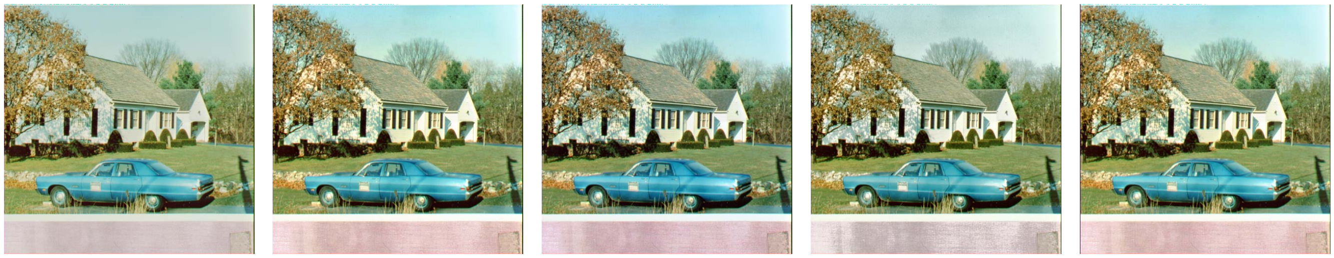
B. Contrast Enhancement Effect and Image Quality

To evaluate the CE effect, the relative contrast error (RCE) defined in [45] is calculated between the original and the enhanced images. Specifically, RCE=0.5 represents the image contrast is unchanged and RCE>0.5 indicates that the image contrast is enhanced. The average results of RCE obtained from the 8 images of USC-SIPI image set, the 24 images of Kodak image set and the 18 images of McMaster image set are shown in Tables I, II and III, respectively. The reason that the iteration time (i.e., time of histogram modification, denoted by n) was set to 80 is as follows. For each image, the maximum iteration time depends on embedding capacity and the amount of side information. That is, the amount of embedded data should be larger than the amount of side information required for image recovery, which is accumulated as n is increased. To evaluate the performance of the four schemes, the embedding capacity of every test image in three sets should be larger than the amount of side information. Meanwhile, the most contrast enhancement effect should be achieved so that n was set to 80.

To assess the quality of the enhanced images, the Peaked Signal-to-Noise Ratio (PSNR), the Structural Similarity index (SSIM) [49] and the blind/referenceless image spatial quality evaluator (BRISQUE) [50] are employed. A larger PSNR represents that the less changes (noise) has been made to the original image. The SSIM index is in the range from 0 to 1, which equals to 1 when the two images are identical to each other. The non-reference BRISQUE score has a typical value between 0 and 100, where 0 represents the best quality and 100 represents the worst. For a high quality image, the BRISQUE score may be even lower than 0. The BRISQUE score is calculated from an enhanced image without referring to the original image, while the PSNR and SSIM index are calculated by comparing the original and enhanced images.

It can be seen in Tables I, II and III that all RCE values are greater than 0.5, demonstrating that the CE effect can be achieved with any of the four schemes. Although the highest RCE values are obtained with the scheme in [14], the corresponding SSIM and PSNR are the lowest, indicating

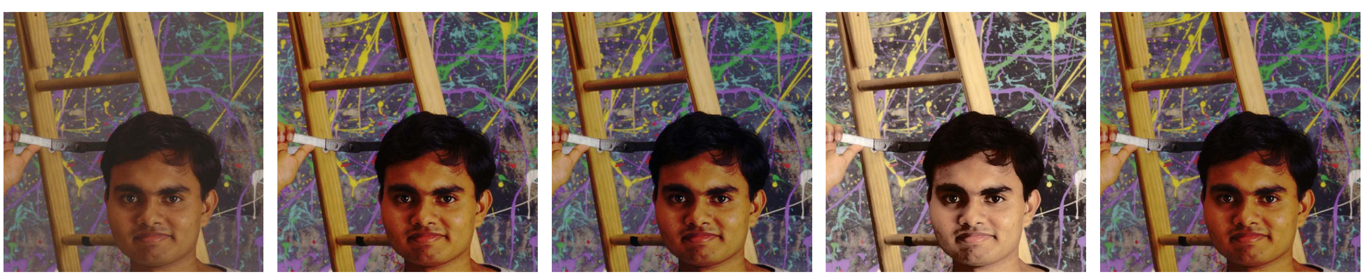
[1]URL: http://sipi.usc.edu/database/database.php?volume=misc
[2]URL: http://www.r0k.us/graphics/kodak/
[3]URL: https://www4.comp.polyu.edu.hk/∼ cslzhang/CDM_Dataset.htm



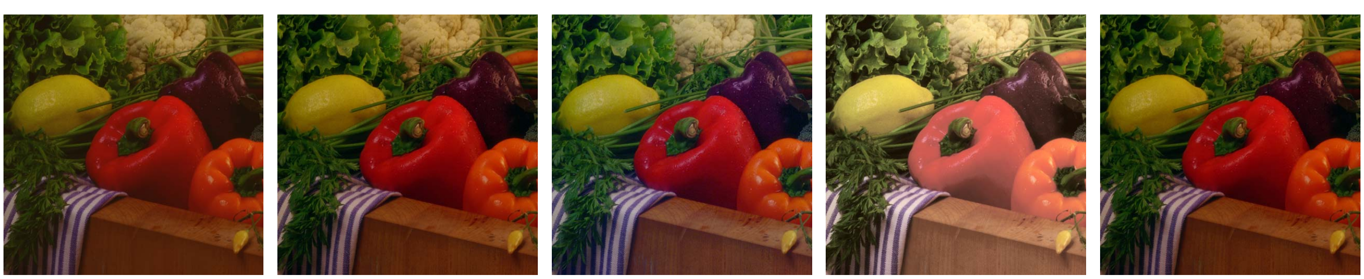
(a) Original image (b) Enhanced by the scheme in [14]. (c) Enhanced by the scheme in [22]. (d) Enhanced by the scheme in [25]. (e) Enhanced by the proposed scheme.

(f) Original image (g) Enhanced by the scheme in [14]. (h) Enhanced by the scheme in [22]. (i) Enhanced by the scheme in [25]. (j) Enhanced by the proposed scheme.

(k) Original image (l) Enhanced by the scheme in [14]. (m) Enhanced by the scheme in [22]. (n) Enhanced by the scheme in [25]. (o) Enhanced by the proposed scheme.



(p) Test image with reduced contrast (q) Enhanced by the scheme in [14]. (r) Enhanced by the scheme in [22]. (s) Enhanced by the scheme in [25]. (t) Enhanced by the proposed scheme.



(u) Test image with reduced contrast (v) Enhanced by the scheme in [14]. (w) Enhanced by the scheme in [22]. (x) Enhanced by the scheme in [25]. (y) Enhanced by the proposed scheme.

Fig. 8. Five test images before and after applying the proposed and the schemes in [14], [22], [25], respectively. The first image is from the USC-SIPI set, the second and the third images are from the Kodak set, while the last two images are from the McMaster set.

that the worst image quality is obtained. Compared with the schemes in [14], [22] and [25], the lower BRISQUE and higher SSIM and PSNR are obtained with the proposed scheme, indicating the better image quality is achieved by modifying the 2D histogram.

C. Brightness Preservation

Brightness difference was used to evaluate the performance of BP, which is the absolute value of difference between average brightness per pixel of the original image and the enhanced one's. The smaller the difference is, the better the

TABLE I

COMPREHENSIVE EVALUATION ON 8 USC-SIPI IMAGES (MEAN) AFTER CONTRAST ENHANCEMENT (N=80)

Scheme	BD	RCE	BRISQUE	SSIM	PSNR(dB)	CIEDE2000	embedding rate(bpp)
[14]	7.007	**0.531**	19.548	0.961	23.573	7.866	**0.480**
[22]	1.772	0.528	16.744	**0.974**	27.615	4.925	0.381
[25]	8.502	**0.531**	17.220	0.947	24.356	**4.302**	0.115
Proposed	**1.691**	0.527	**16.346**	**0.974**	**27.720**	4.847	0.375

TABLE II

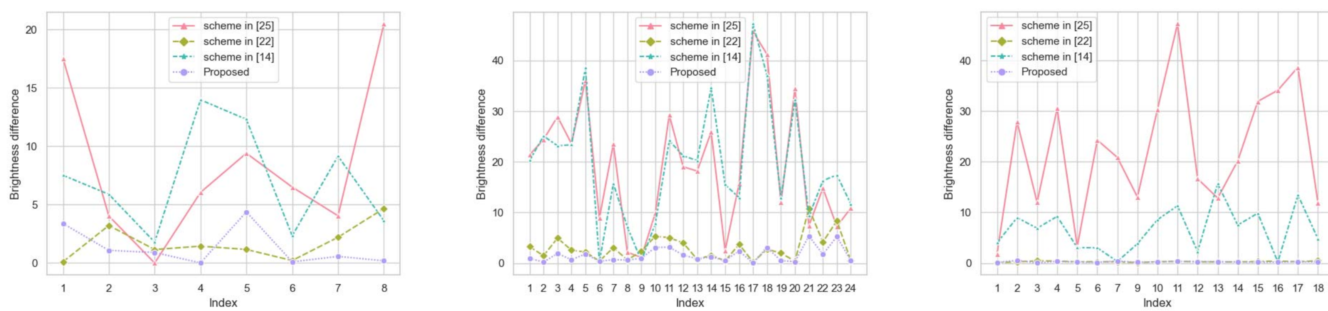
COMPREHENSIVE EVALUATION ON 24 KODAK IMAGES (MEAN) AFTER CONTRAST ENHANCEMENT (N=80)

Scheme	BD	RCE	BRISQUE	SSIM	PSNR(dB)	CIEDE2000	embedding rate(bpp)
[14]	8.466	**0.537**	14.878	0.933	22.361	9.831	**0.554**
[22]	1.675	0.530	12.727	**0.959**	29.713	4.660	0.382
[25]	10.744	**0.537**	14.847	0.917	22.954	5.045	0.180
Proposed	**1.404**	0.530	**7.871**	**0.959**	**30.244**	**4.551**	0.371

TABLE III

COMPREHENSIVE EVALUATION ON 18 MCMASTER IMAGES (MEAN) AFTER CONTRAST ENHANCEMENT (N=80)

Scheme	BD	RCE	BRISQUE	SSIM	PSNR(dB)	CIEDE2000	embedding rate(bpp)
[14]	6.260	0.508	**16.981**	0.892	23.013	6.775	**0.811**
[22]	0.252	0.533	17.992	**0.957**	27.700	**4.437**	0.789
[25]	22.206	**0.583**	18.593	0.849	17.774	9.049	0.303
Proposed	**0.231**	0.533	17.410	**0.956**	**27.735**	**4.466**	0.715



(a) USC-SIPI images (b) Kodak images (c) McMaster images

Fig. 9. Brightness difference between an original image and its contrast-enhanced image by applying schemes in [14], [22], [25] and the proposed scheme with a fixed time of histogram modification (n=80). The horizontal axis represents index of every test image in each set, and the vertical axis represents difference of brightness.

brightness is preserved. To compare the performance, all of the four schemes were conducted on every test image in the three sets, respectively. The time of histogram modification was set as mentioned in Section IV-A.

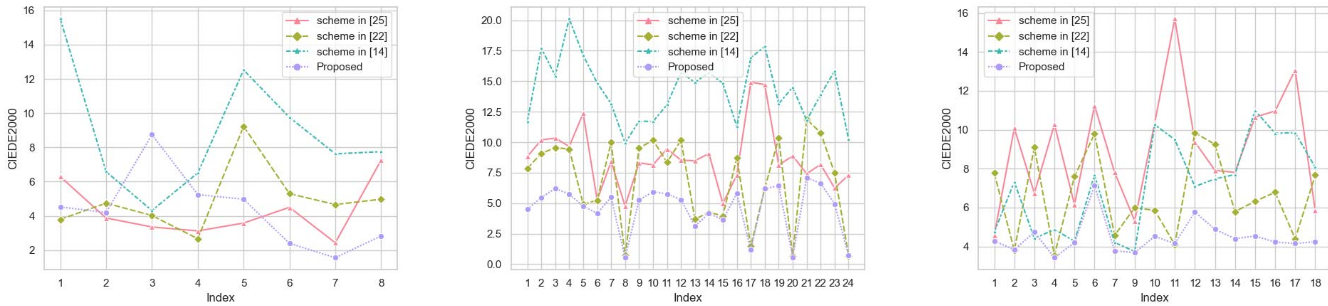
As shown in Fig. 9, the brightness difference was obtained from every test image of three image sets after applying the proposed scheme and those in [14], [22] and [25]. The curves corresponding to the proposed scheme are always under the other curves, indicating that the least brightness difference was introduced by applying the proposed scheme. The reason is that the fine adjustment of image brightness can be achieved by modifying the 2D histogram.

To further compare the BP performance, the statistical results on three test image sets obtained with the four schemes are shown in Tables I, II and III, respectively. Each item in the tables is the mean of 8, 24 or 18 test images. From the listed BD values, it can be seen that the schemes in [14] and [25] largely changed the image mean brightness. Compared with the results obtained with the scheme in [22], averagely lower BD values were achieved with the proposed scheme.

D. Color Preservation

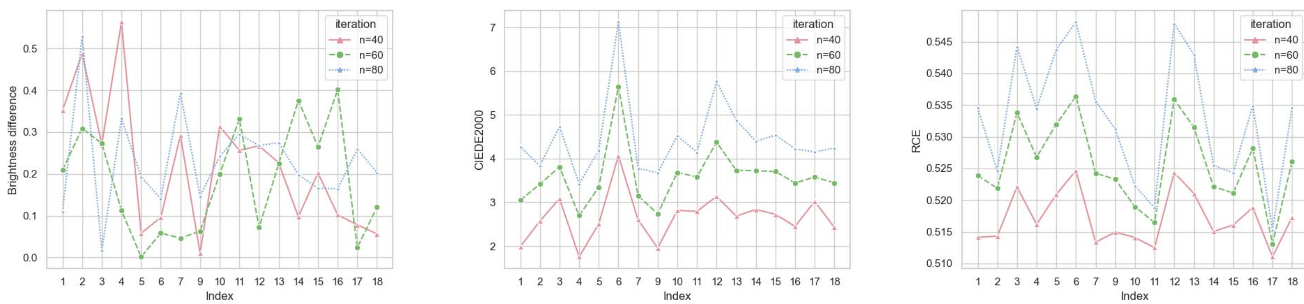
CIEDE2000 [51] is often used as an indicator of color retention, which value is expected to be as small as possible to avoid color distortion. Fig. 10 shows the CIEDE2000 value for every test image in three image sets after applying the four schemes. The curves corresponding to the proposed scheme are generally lower than the other curves, showing that the proposed scheme has the least impact on original image color. Although the HSV color model is adopted in [25] for CE-RDH, the proposed scheme sometimes outperforms Guan's scheme in color preservation due to fine adjustment of pixel values by 2D histogram modification.

The average CIEDE2000 obtained by applying the four schemes on three image sets are also listed in Tables I, II and III, respectively. It can be seen that Guan's scheme [25] generally performs better on USI-SIPI image set. Meanwhile, less color distortions are introduced by applying the proposed scheme on the images in Kodak dataset and McMaster dataset, respectively. To further evaluate the performance, the proposed scheme was applied on the



(a) USC-SIPI images (b) Kodak images (c) McMaster images

Fig. 10. CIEDE2000 of test images after applying schemes in [14], [22], [25] and the proposed scheme with a fixed time of histogram modification (n=80). The horizontal axis represents index of every test image in each set.



(a) Brightness difference of enhanced images with respect to iteration time. (b) CIEDE2000 of enhanced images with respect to iteration time. (c) RCE of enhanced images with respect to iteration time.

Fig. 11. Different metrics calculated from the images enhanced with the proposed scheme for different time of histogram modification. The horizontal axis represents index of every test image in the McMaster set.

McMaster images by setting different times of histogram modification (i.e., n). Three metrics (i.e., brightness difference, CIEDE2000, RCE) were calculated from the enhanced McMaster test images and illustrated in Fig. 11, respectively. From the curves illustrated in Fig. 11, it can be seen that there is a trade-off between color preservation (indicated by CIEDE2000) and contrast enhancement (indicated by RCE) because both CIEDE2000 and RCE values were increased with n. Meanwhile, the change of brightness is much less related to n, indicating that the proposed scheme has good performance in brightness preservation.

E. Embedding Rate

In Tables I, II and III, the corresponding average embedding rates on the three image sets are listed. With each of these four schemes, extra bit values were embedded in the enhanced images besides the side information. By subtracting the bit number of side information from the totally embedded bits, the pure hiding rate was calculated by dividing the number of extra bits with the pixel number in the whole image. So the obtained embedding rate is represented in bit per pixel (bpp in short). The ACERDH scheme [14] provides the maximum embedding rate, but leads to serious color and brightness distortion. The close embedding rates were obtained with the schemes in [22] and [25] and the proposed one, respectively.

F. Security Analysis

The security of the proposed algorithm in the applications of image reversible contrast enhancement relies on the order of scanning pixels to modify the 2D histogram, which can be controlled by using a secret key. In modifying each row or column of histogram bins, the pixel pairs contained in those bins need to be found out by scanning the whole image. Without the correct key, it is hard to determine the order of scanning pixel pairs to restore each row or column of the 2D histogram. As a result, it is even harder to correctly extract the hidden data and recover the original image. Suppose that m_i pixels are selected to carry the embedded data in the $i^{th}(1 \leq i \leq n)$ iteration where n represents the time of histogram modification, so there are $m_i!$ possible scanning orders in the i^{th} iteration and $\prod_{i=1}^{n} m_i!$ possible extracted results totally. If an attacker does not know the secret key and attends to extract embedded data from the enhanced image correctly, the computational complexity will be $O(\prod_{i=1}^{n} m_i!)$.

G. Computational Complexity

Suppose that there are totally m pixels in the original image and histogram modification is iteratively performed by n times. Since every pixel is scanned in 2D histogram generation and histogram modification, the computational complexity of 2D histogram generation and histogram modification is $O(m)$. The number of operations in BP will not be more than that of 2D histogram generation and histogram modification, so the computational complexity of the proposed scheme is $O(mn)$. Since every pixel needs to be scanned to generate and modify a 1D histogram, the computational complexity of schemes in [14], [22] and [25] is also $O(mn)$.

V. Conclusion

In this paper, we have proposed a new reversible data hiding scheme with brightness preserving contrast enhancement by generating and modifying a two-dimensional histogram. A new strategy has been developed to adaptively modify and shift rows or columns of histogram bins at each iteration. The row or column of histogram bins containing the maximum number of pixel pairs are expanded for data embedding, while the row or column of histogram bins with the minimum number of pixel pairs are chosen to be merged with the adjacent one. To avoid over enhancement, a stopping condition has been defined so that an automatic contrast enhancement procedure can be performed. Since fine adjustment can be achieved by performing histogram modification in two-dimensional plane, the comparable contrast enhancement effect is obtained with the proposed scheme while achieving better image quality. Besides reversibility of image contrast enhancement, statistical experimental results on three image sets clearly show that better brightness preservation and color preservation can be achieved by applying the proposed scheme.

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