Digital Signal Processing 136 (2023) 103965

Contents lists available at ScienceDirect

Digital Signal Processing

journal homepage: www.elsevier.com/locate/dsp

A hue preservation lossless contrast enhancement method with RDH for color images

Guangyong Gao [a,b,c,d], Tingting Han [a,b], Bin Wu [d,*], Jiaxin Fu [a,b], Zhihua Xia [e]

[a] Engineering Research Center of Digital Forensics, Ministry of Education, Nanjing University of Information Science & Technology, Nanjing, 210044, China
[b] School of Computer Science, Nanjing University of Information Science & Technology, Nanjing, 210044, China
[c] Xinda Institute of Advanced Technology, Zhengzhou, 450001, China
[d] School of Computer and Big Data Science, Jiujiang University, Jiujiang, Jiangxi 332005, China
[e] College of Cyber Security, Jinan University, Guangzhou, 510632, China

ARTICLE INFO

Article history:
Available online 10 February 2023

Keywords:
Data hiding
Contrast enhancement
Hue preservation
Color images
CIEDE2000 metric

ABSTRACT

The contrast enhancement with reversible data hiding (CERDH) has become a hot topic in many fields. At present, most schemes applying CERDH methods to color images have the problem of color distortion. To solve this problem, this paper proposes a CERDH method for color images based on constant hue plane. It firstly separates the color images into min, mid and max channels. Then, a novel preprocessing is proposed to maintain the distribution of histogram for original image while vacate room for data hiding. After that, the mid channel is used for data hiding, and min and max channels are hue-preserved to avoid color distortion. Finally, the three channels compose a contrast-enhanced color image. The experimental results show that the proposed method achieves the best enhanced results based on CIEDE2000 compared with the state-of-the-art methods, and color distortion is also greatly reduced.

1. Introduction

With the rapid development of Internet technology, the information privacy leaks, identity theft and illegal copying have made reversible data hiding methods receive widespread attention [1]. The reversible data hiding (RDH) is firstly proposed in [2]. RDH is a kind of information hiding technology that can hide secret information into media data to achieve the purposes of secret communication and copyright protection of information, and can recover the original carrier after extracting secret information. In the domain of image processing, different techniques are combined with RDH to achieve larger payload or better image quality. Interpolation technique is used to preserve high quality of the images in [3]. Difference expansion [4], prediction error [5] and histogram shifting [6] are also utilized to achieve the purpose of reducing distortion after embedding. The RDH is usually used in the field of military or medicine which needs high image quality.

On the basis of broadening the application field of RDH, Wu et al. [7] developed the RDH from a new perspective which is called contrast enhancement with reversible data hiding (CERDH), which can enhance the contrast of the carrier image while hiding large amounts of data. The aim of CERDH is to achieve histogram equalization, and it has been said that an image with higher contrast usually has uniform distribution on its histogram. In other words, if the histogram of an image could cover [0, 255], then the image has high contrast.

Soon after, CERDH technique develops rapidly. Gao et al. [8] achieved controlled contrast enhancement by integer wavelet transform. Adaptive histogram shifting and pixel value ordering are used to achieve higher contrast [9], and another adaptive contrast enhancement is proposed by Kim et al. [10]. In recent years, researchers begin to focus on human vision system to further improve the performance of contrast enhancement [11,12]. In other fields like medical or military community, those images usually have low contrast and they are viewed as the best object to conduct contrast enhancement. Gao et al. [13] provided tamper localization for medical images to prevent the hackers' attack. For medical images, the poor effect of conducting CERDH to medical images directly is obvious. Therefore, scholars begin to separate the medical images into regions of interest (ROI) and regions of non-interest (NROI). Yang et al. [14] proposed a method which firstly separates ROI and NROI in medical images by adaptive threshold detector, then it stretches histogram to achieve the effect of contrast enhancement. Gao et al. [15] improved Yang's method by automatically stretching histogram and it obtains larger embedding capacity and higher contrast. In recent years, the protection of patients' privacy becomes a hot topic. Therefore, the encryption

* Corresponding author.
E-mail address: wubcst@163.com (B. Wu).

https://doi.org/10.1016/j.dsp.2023.103965
1051-2004/

technique [16] is combined with CERDH and several algorithms are proposed [17,18].

The previously mentioned methods are all designed for grayscale images which are also called single channel images. However, the CERDH for color images is difficult to achieve, because the color distortion is very easily encountered. Not similar to grayscale images, the color images have three channels which are known as red channel, green channel and blue channel (RGB). Grayscale images own a single pixel attribute, while color images own more attributes such as hue and saturation. The color of the pixel is determined by hue, and the degree to which the color approximates the spectral color is determined by saturation. It is well known that contrast enhancement in color images has developed rapidly over the past few decades. For fuzzy images, Veluchamy et al. [19] applied histogram equalization to color images and achieved color correction simultaneously. A fuzzy c-means clustering-based method for image enhancement is proposed in [20], and a method for nearly invisible underwater images is proposed in [21]. Ueda et al. [22] proposed a plane where the colors on it have the same hue, and they achieve good enhanced results based on that plane.

Although the color image contrast enhancement realizes great achievement, its application is hard to be combined with RDH. The reason is that the reversibility for those modified pixels in color images is hard to retain. References [23–26] proposed several methods that combine RDH with contrast enhancement for color images, but the enhanced images quality still needs to be improved. For example, in [23] and [24], the enhanced images did not preserve the hue of the original images. To sum up, although the above CERDH schemes achieve better image contrast enhancement, these schemes do not take into account the impact of hue preservation and brightness difference maintenance between three channels on the results, so these images suffer from details distortion and color distortion.

To avoid the problem of color distortion and improve the quality of enhanced results, a lossless contrast enhancement method for color images with reversible data hiding based on constant hue plane (LCECRDH-CHP) is proposed in this paper. As far as we know, in the proposed method, a novel preprocessing is proposed to maintain the distribution of histogram for original image, and the constant hue plane is firstly proposed to solve the problem of color distortion in domain of CERDH. Moreover, an effective metric called CIEDE2000 [27] is used to measure visual quality of the enhanced color images based on the different visual perceptions in the three channels. Finally, the proposed method achieves the best CIEDE2000 results, and the restored images are very similar to the original images with PSNR being around 50 dB. The contributions can be summarized as follows:

1) A novel preprocessing is proposed in this paper, it can maintain the distribution of histogram for original image while vacate room for data hiding. As a result, it leads to no visual distortion in the enhanced image.

2) The min channel is the darkest channel and the max channel is the brightest channel of an image. In order to achieve better visual quality, the mid channel is innovatively selected to conduct data hiding and contrast enhancement. As a result, the enhanced images have similar brightness to the original images.

3) A hue preservation operation based on constant hue plane is innovatively applied to RDH in this paper. Thus, the hue of enhanced images is same with that of original images and no color distortion is introduced, which is also reflected by CIEDE2000 results.

The rest of this paper is organized as follows. Section 2 introduces related work. Section 3 introduces the proposed method in details. Experimental results are presented in Section 4 and conclusions are summarized in Section 5.

2. Related work

There is already many CERDH methods for grayscale images, but there is few CERDH methods for color images, most methods only enhance the color images without embedding secret message, which is important for the field of data hiding.

As far as we know, Kim et al. [23] proposed a method for Automatic Brightness Preserving Contrast Enhancement with Reversible Data Hiding (ABPCERDH). In this method, the color image is separated into R, G and B channels firstly. Then, the secret message is embedded into each channel. Histogram shifting is conducted to achieve data hiding. For every repetition of the histogram shifting, splitting bin P_s and combining bin P_c are chosen. There are two types of shifting defined which are right histogram shifting (RHS) and left histogram shifting (LHS). The shortcoming of this method is that it directly enhances R, G and B channels and does not consider the color distortion problem. Although the shifting is controlled to decrease this problem, the color distortion is still visible. Similarly, Zhang et al. [24] proposed a method to enhance contrast based on multi-histogram modification. Wu et al. [25] proposed a method for Lossless Contrast Enhancement of Color images with Reversible Data Hiding (LCECRDH). The human visual system is introduced in this method, and it explains that the human visual system characterizes a color image by its brightness and chromaticity [28]. And it introduced hue, saturation and value (HSV) color space, the transformed equation from RGB to HSV is fully studied and the enhanced image achieves hue preservation. The transformation from RGB to HSV includes decimal calculation, and the pixel values are unable to be restored as the original pixel values because of the so-called truncation error. The drawback of this method is that the max channel is selected to conduct contrast enhancement. Because the max channel is the brightest channel of an image, the enhanced image will be too bright. The effect of contrast enhancement will be poor.

Wu et al. [26] proposed a method for Reversible Contrast Enhancement scheme for Color images (RCEC). This method improves the LCECRDH to achieve better effect of contrast enhancement. As a result, the hue preservation is achieved. Reversible Data Hiding with Brightness Preserving Contrast Enhancement (RDHBPCE) by two-dimensional histogram modification was proposed [29]. This scheme preserved image color and brightness. However, from the experimental results of [26] and [29], there are still details distortion, and the enhanced image quality can still be further improved.

To solve these problems, we propose a new preprocessing method, and innovatively put forward a constant hue plane to solve the distortion problem.

3. Proposed algorithm

A new lossless contrast enhancement method for color images with reversible data hiding based on constant hue plane (LCECRDH-CHP) is proposed in this paper. The encoding and decoding of the proposed method are shown in Fig. 1 and Fig. 2. In the encoding phase, the original image I is firstly preprocessed. Then, the preprocessed image I_p is separated into three channels: max channel $I_{p\text{-}max}$, mid channel $I_{p\text{-}mid}$ and min channel $I_{p\text{-}min}$. The $I_{p\text{-}mid}$ is selected to embed the secret message. After that, the $I_{p\text{-}max}$ and $I_{p\text{-}min}$ are hue-preserved according to the theory of constant hue plane. Finally, the enhanced color image I_E is obtained by combining the embedded mid channel $I_{e\text{-}mid}$, hue-preserved max channel $I_{hp\text{-}max}$ and hue-preserved min channel $I_{hp\text{-}min}$. In the decoding phase, the I_E is firstly separated into three enhanced channels: enhanced mid channel $I_{E\text{-}mid}$, enhanced max channel $I_{E\text{-}max}$ and enhanced min channel $I_{E\text{-}min}$. Then, the secret message can be extracted from the $I_{E\text{-}mid}$, and the $I_{E\text{-}max}$

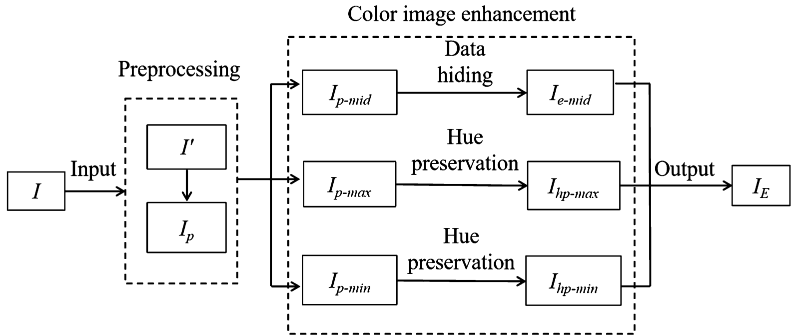


Fig. 1. The proposed scheme of encoding.

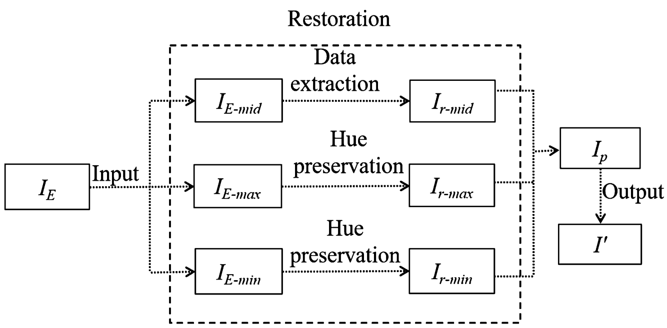


Fig. 2. The proposed scheme of decoding.

and $I_{E\text{-}min}$ are restored with hue preservation. After that, the restored image I_r which is equal to I_p can be obtained by combining the three restored channels which are restored mid channel $I_{r\text{-}mid}$, restored max channel $I_{r\text{-}max}$ and restored min channel $I_{r\text{-}min}$. Finally, the size-preserved image I', which is very similar to I, can be obtained by mapping. The notations in this paper and their corresponding descriptions are presented in Table 1.

3.1. Image preprocessing

The preprocessing in the proposed method slightly modifies some pixel values of the original image, and enough room is vacated in I_p for data hiding. Meanwhile, the pixel distribution of original histogram is preserved because of the mapping operation. Thus, the visual distortion is avoided. The purpose of preprocessing is vacating S bins in each side of I, in order to achieve this, the proposed method firstly separates the I into I_{min}, I_{mid} and I_{max}. Then, the size relationship preservation operation is conducted on I to generate I'. Finally, the mapping operation is further conducted on I' to generate I_p. The length of the embedded secret information is determined by the input parameter S during preprocessing, and the embedding capacity of each image is different. The embedded capacity increases with the increase of S. For example, experiments show that if S is equal to 10 and 20, the average embedding capacity of Kodak images is 1263 bits and 13657 bits, respectively. The detailed preprocessing is shown in Fig. 3, where I'_{max}, I'_{mid} and I'_{min} are the max, mid and min channels of I', and $I_{p\text{-}max}$, $I_{p\text{-}mid}$ and $I_{p\text{-}min}$ are the max, mid and min channels of I_p, respectively.

In details, each pixel $I(i, j)$ of I will be separated into the max value $I_{max}(i, j)$, the mid value $I_{mid}(i, j)$ and the min value $I_{min}(i, j)$. The max value, mid value and min value in $I_p(i, j)$ are denoted as $I_{p\text{-}max}(i, j)$, $I_{p\text{-}mid}(i, j)$ and $I_{p\text{-}min}(i, j)$, and the mapping operation must retain the size relationship between each value of $I(i, j)$ and $I_p(i, j)$, which is explained by an example in Fig. 4, where the subscripts r, g and b represent the red, green and blue values of each pixel, respectively. It can be observed from Fig. 4 that the $I_r(i, j)$ is the max value in $I(i, j)$ originally. However, the $I_r(i, j)$ and $I_g(i, j)$ are equal after directly mapping, which means that red is primary color in original pixel compared with red and green being primary colors in $I_p(i, j)$. This will lead to color distortion which is a disallowed problem. Therefore, the size relationship preservation is firstly conducted before mapping to avoid this problem.

Given S ($0 < S \leq 50$) bins which need to be vacated, the basic mapping operation in the proposed method is conducted by Eq. (1),

$$Value_{mapping} = round\left[\frac{Value_{origin}}{255} \times (255 - S \times 2) + S\right], \quad (1)$$

where the $Value_{origin}$ is the original pixel value, the $Value_{mapping}$ is the mapping pixel value, and the $Value_{mapping}$ of pixel value x can be obtained by $M_S(x)$. According to Eq. (1), the mapping table can be obtained. The mapping tables with $S = 10$, 20 and 30 are shown in Table 2, Table 3 and Table 4 as examples, respectively. It is observed from Table 3 that the $Value_{origin}$ 3 and 4 are mapped to $Value_{mapping}$ 23 (i.e. $M_{20}(3) = M_{20}(4) = 23$), and $Value_{origin}$ 251 and 252 are mapped to $Value_{mapping}$ 232 (i.e. $M_{20}(251) = M_{20}(252) = 232$). The similar condition occurs in Table 4. These conditions will lead to the color distortion mentioned above.

Table 1
Notations and parameters of algorithm.

Notation	Description	Notation	Description	Notation	Description
I_p	preprocessed image	I_E	enhanced color image	$I_{E\text{-}mid}$	mid channel of the enhanced color image
$I_{p\text{-}max}$	max channel of the preprocessed image	$I_{e\text{-}mid}$	mid channel after embedding information	$I_{E\text{-}max}$	max channel of the enhanced color image
$I_{p\text{-}mid}$	mid channel of the preprocessed image	$I_{hp\text{-}max}$	hue-preserved max channel	$I_{E\text{-}min}$	min channel of the enhanced color image
$I_{p\text{-}min}$	min channel of the preprocessed image	$I_{hp\text{-}min}$	hue-preserved min channel	I'	size-preserved image
I_r	restored image	$I_{r\text{-}max}$	restored max channel	I	original image
$I_{r\text{-}mid}$	restored mid channel $I_{r\text{-}mid}$	$I_{r\text{-}min}$	restored min channel		

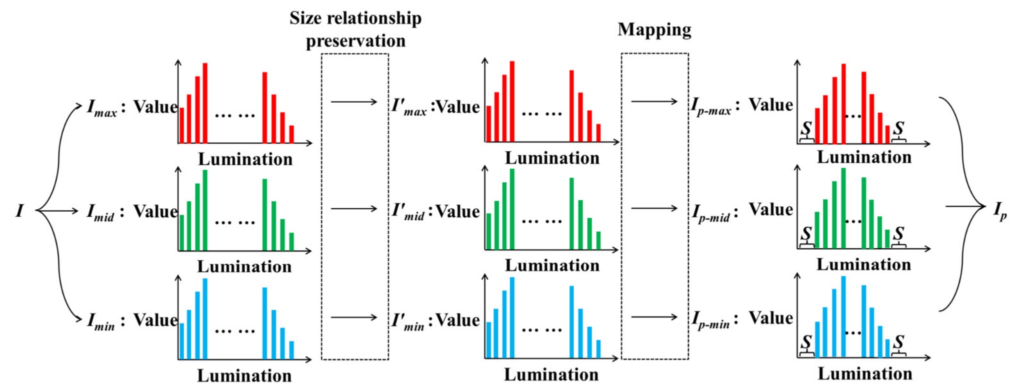


Fig. 3. Details of the proposed preprocessing.

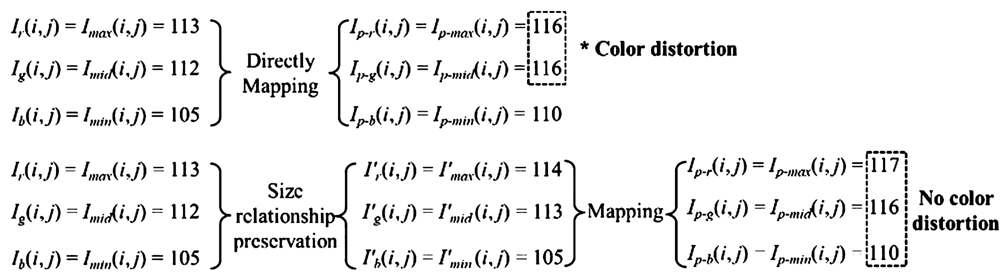


Fig. 4. An example for explaining the size relationship between $I(i, j)$ and $Ip(i, j)$.

Table 2
Mapping values with S = 10.

$Value_{origin}$	0	1	2	3	4	...	251	252	253	254	255
$Value_{mapping}$	10	11	12	13	14	...	241	242	243	244	245

Table 3
Mapping values with S = 20.

$Value_{origin}$	0	1	2	3	4	...	251	252	253	254	255
$Value_{mapping}$	20	21	22	23	23	...	232	232	233	234	235

Table 4
Mapping values with S = 30.

$Value_{origin}$	0	1	2	3	4	...	251	252	253	254	255
$Value_{mapping}$	30	31	32	32	33	...	222	223	223	224	225

In order to solve this problem, the size relationship preservation is conducted according to the mapping table with certain S, which is shown as follows:

$$\{x', y', z'\} = \begin{cases} \{x, y-1, z-1\}, \\ if\ \ (x \neq y \neq z \text{ and } M_S(x) \neq M_S(y) = M_S(z)) \\ \text{or } \ (x = y \neq z \text{ and } M_S(x) = M_S(y) = M_S(z)) \\ \{x+1, y+1, z\}, \\ if\ \ (x \neq y \neq z \text{ and } M_S(x) = M_S(y) \neq M_S(z)) \\ \text{or } \ (x \neq y = z \text{ and } M_S(x) = M_S(y) = M_S(z)) \\ \{x, y, z\}, \text{ else}, \end{cases} \tag{2}$$

where $\{x, y, z\}$ and $\{x', y', z'\}$ represent $\{I_{max}(i, j), I_{mid}(i, j), I_{min}(i, j)\}$ and $\{I'_{max}(i, j), I'_{mid}(i, j), I'_{min}(i, j)\}$, respectively. The proof of Eq. (2) is presented in the appendix. Finally, the I_p is generated by mapping the I' by Eq. (3),

$$I_p(i, j) = round\left[\frac{I'(i, j)}{255} \times (255 - S \times 2) + S\right]. \tag{3}$$

3.2. Data hiding

The scheme of data hiding applies the method in [30], and the $I_{p\text{-}mid}$ is embedded with the secret message according to that method to generate $I_{e\text{-}mid}$. By denoting the values of the highest two bins as f_L and f_R ($f_L < f_R$), a pixel value $I_{p\text{-}mid}(i, j)$ in the $I_{p\text{-}mid}$ is modified to $I_{e\text{-}mid}(i, j)$ by

$$I_{e\text{-}mid}(i, j) = \begin{cases} I_{p\text{-}mid}(i, j) - 1, & \text{if } I_{p\text{-}mid}(i, j) < f_L \\ I_{p\text{-}mid}(i, j) - b_i, & \text{if } I_{p\text{-}mid}(i, j) = f_L \\ I_{p\text{-}mid}(i, j), & \text{if } f_L < I_{p\text{-}mid}(i, j) < f_R \\ I_{p\text{-}mid}(i, j) + b_i, & \text{if } I_{p\text{-}mid}(i, j) = f_R \\ I_{p\text{-}mid}(i, j) + 1, & \text{if } I_{p\text{-}mid}(i, j) > f_R \end{cases} \tag{4}$$

where b_i is the ith value in secret message. The number of bins to vacate S is embedded together the secret message. By repeatedly splitting each of the highest two bins into two adjacent bins for data hiding, the histogram equalization effects can be obtained.

3.3. Hue preservation

Hue preservation is a significant issue in color image enhancement. If the hue of a pixel is changed, then the color of the pixel is changed. The enhanced image will introduce more color distortion if more pixels are not hue-preserved. To solve this problem, the constant hue plane is proposed as a plane in the RGB color space where the pixels have the same hue. If an enhanced pixel and its original pixel are on the same constant hue plane, then they can be defined as having the same hue. An example for a constant hue plane in RGB color space is shown in Fig. 5.

It is defined that a pixel p in RGB color space is consisted of (p_r, p_g, p_b) and $p_r, p_g, p_b \in [0, 255]$, then k is the black color $(0, 0, 0)$ and w is the white color $(255, 255, 255)$. The c is defined as the maximally saturated color which is consisted of (c_r, c_g, c_b), and (c_r, c_g, c_b) are calculated as:

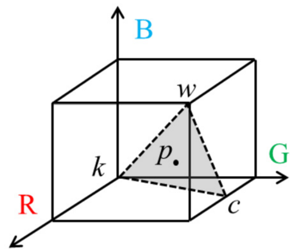


Fig. 5. An example for a constant hue plane in RGB color space.

$$\begin{cases} c_r = round[\dfrac{p_r - min(p)}{max(p) - min(p)} \times 255] \\ c_g = round[\dfrac{p_g - min(p)}{max(p) - min(p)} \times 255] \\ c_b = round[\dfrac{p_b - min(p)}{max(p) - min(p)} \times 255] \end{cases}, \tag{5}$$

where $max(p)$ obtains the maximum value of p and $min(p)$ obtains the minimum value of p. The k, w and c compose the constant hue plane of p, and all the pixels in this plane have the same hue with p.

The technique of constant hue plane can be perfectly applied to color image enhancement to solve the problem of hue preservation. From Eq. (5), it is easy to conclude that the denominators are all defined as $max(p) - min(p)$. When one element in (p_r, p_g, p_b) is changed, the other two elements need to be changed by the same magnitude so that the enhanced pixel has the same hue as the original pixel. Specifically speaking, the hue preservation equation in the proposed method can be defined by Eq. (6) and Eq. (7) as:

$$amplitude = \begin{cases} p'_r - p_r, & \text{if } p_r \text{ is changed} \\ p'_g - p_g, & \text{if } p_g \text{ is changed} \\ p'_b - p_b, & \text{if } p_b \text{ is changed} \\ 0, & \text{else} \end{cases} \tag{6}$$

$$\begin{cases} p'_r = p_r + amplitude \\ p'_g = p_g + amplitude \\ p'_b = p_b + amplitude \end{cases}, \tag{7}$$

where the hue-preserved pixel p' is consisted of (p'_r, p'_g, p'_b).

In the proposed method, the mid channel is selected to conduct data hiding. Therefore, the original pixel value $I_{p\text{-}mid}(i, j)$ is changed as $I_{e\text{-}mid}(i, j)$, and the changed amplitude is calculated as $I_{e\text{-}mid}(i, j) - I_{p\text{-}mid}(i, j)$. Thus, the hue-preserved min channel and max channel are calculated by Eq. (8) as:

$$\begin{cases} I_{hp\text{-}min}(i, j) = I_{p\text{-}min}(i, j) + (I_{e\text{-}mid}(i, j) - I_{p\text{-}mid}(i, j)) \\ I_{hp\text{-}max}(i, j) = I_{p\text{-}max}(i, j) + (I_{e\text{-}mid}(i, j) - I_{p\text{-}mid}(i, j)), \end{cases} \tag{8}$$

where $I_{hp\text{-}max}(i, j)$ and $I_{hp\text{-}min}(i, j)$ are the pixel values of hue-preserved max channel and hue-preserved min channel, respectively. Finally, three channels which are $I_{e\text{-}mid}$, $I_{hp\text{-}max}$ and $I_{hp\text{-}min}$ are combined to construct the enhanced color image I_E. An algorithm is presented below to explain the details of the proposed hue preservation.

Algorithm 1 Hue preservation.

Input: $m \times n$ preprocessed image I_p; embedded mid channel $I_{e\text{-}mid}$;
Output: Enhanced image I_E;

```
1: I_p-min(i, j), I_p-mid(i, j) and I_p-max(i, j) ← I_p
2:   for i ← 1 to m do
3:     for j ← 1 to n do
4:       I_hp-min(i, j) = I_p-min(i, j) + (I_e-mid(i, j) − I_p-mid(i, j))
5:       I_hp-max(i, j) = I_p-max(i, j) + (I_e-mid(i, j) − I_p-mid(i, j))
6: Return I_E ← I_e-mid, I_hp-min and I_hp-max
```

3.4. Data extraction and image restoration

The proposed method can extract the secret message losslessly and restore the color image very similar to the original image. Given the I_E, the I_E is firstly separated into min channel $I_{E\text{-}min}$, mid channel $I_{E\text{-}mid}$ and max channel $I_{E\text{-}max}$. Then, the secret message and S can be extracted from $I_{E\text{-}mid}$, and the restored mid channel $I_{r\text{-}mid}$ is achieved according to method [30].

With the enhanced channel $I_{E\text{-}mid}$ and the restored channel $I_{r\text{-}mid}$, the $I_{E\text{-}min}$ and $I_{E\text{-}max}$ can be restored by Eq. (9) as:

$$\begin{cases} I_{r\text{-}min}(i, j) = I_{E\text{-}min} + (I_{r\text{-}mid}(i, j) - I_{E\text{-}mid}(i, j)) \\ I_{r\text{-}max}(i, j) = I_{E\text{-}max} + (I_{r\text{-}mid}(i, j) - I_{E\text{-}mid}(i, j)) \end{cases}, \tag{9}$$

where $I_{r\text{-}min}(i, j)$ and $I_{r\text{-}max}(i, j)$ are the pixel values of restored min channel and max channel, respectively. Then, the restored image I_r is obtained by combining three restored channels, and the I_r is equal to I_p.

Finally, the inverse mapping is conducted to I_r to obtain the I' which is very similar to the original image. The inverse mapping equation is shown in Eq. (10) as:

$$I'(i, j) = round\left[\frac{I_r(i, j) - S}{255 - S \times 2} \times 255\right]. \tag{10}$$

4. Experimental results

In this section, the enhanced images of the ABPCERDH [23], CERDHMM [24], LCECRDH [25], RCEC [26], RDHBPCE [29] and the proposed method are firstly compared to subjectively show the better visual quality of ours. Then, the statistical analysis, including PSNR, SSIM, Mean Opinion Score (MOS) and CIEDE2000 are used to objectively show the performance of the proposed method.

The equations of PSNR are as follows:

$$MSE = \frac{1}{mn}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i, j) - K(i, j)]^2 \tag{11}$$

$$PSNR = 10 \cdot \log_{10}(\frac{MAX_I^2}{MSE}), \tag{12}$$

where MSE stands for meansquare error of the current image and the reference image. $I(i, j)$ and $K(i, j)$ respectively stand for the pixel values at the corresponding coordinates, and m and n respectively stand for the height and width of the image. MAX_I^2 is the maximum pixel value of the image.

The equation of SSIM is as follows:

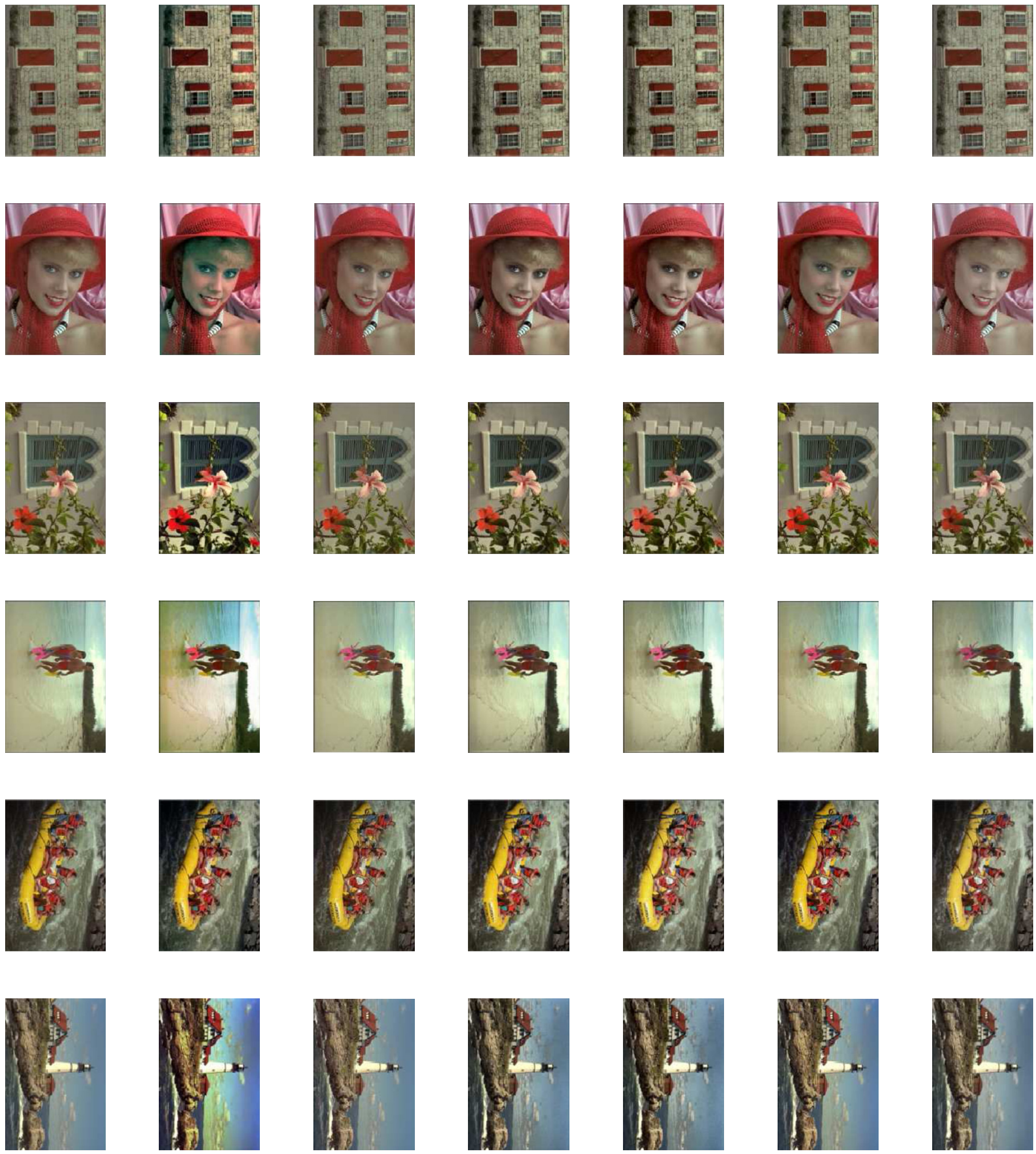
$$SSIM(X, Y) = \frac{(2u_X u_Y + C_1)(2\sigma_{XY} + C_2)}{(u_X^2 + u_Y^2 + C_1)(\sigma_X^2 + \sigma_Y^2 + C_2)}, \tag{13}$$

where u_X and u_Y represent the mean values of image X and Y respectively, σ_X, σ_Y represents the standard deviation of image X and Y respectively, and σ_{XY} is the covariance of X and Y.

The equation of CIEDE2000 is as follows:

$$\Delta E_{00} = [(\frac{\Delta L'}{k_L S_L})^2 + (\frac{\Delta C'}{k_C S_C})^2 + (\frac{\Delta H'}{k_H S_H})^2 + R_T(\frac{\Delta C'}{k_C S_C})(\frac{\Delta H'}{k_H S_H})]^{1/2}. \tag{14}$$

Where $\Delta L'$, $\Delta C'$ and $\Delta H'$ represent brightness difference, chroma difference and hue difference respectively. K_L, K_C and K_H



(a) Original (b) ABPCERDH (c) CERDHMM (d) LCECRDH (e) RCEC (f) RDHBPCE (g) Proposed

Fig. 6. Comparisons of enhanced images on Kodak.

are brightness weight factor, chrominance weight factor and hue weight factor respectively. S_L, S_C and S_H are brightness correction, chrominance correction and hue correction respectively. R_T is a rotation function. It's correcting the direction of the main axis of the elliptic anticipating the blue region.

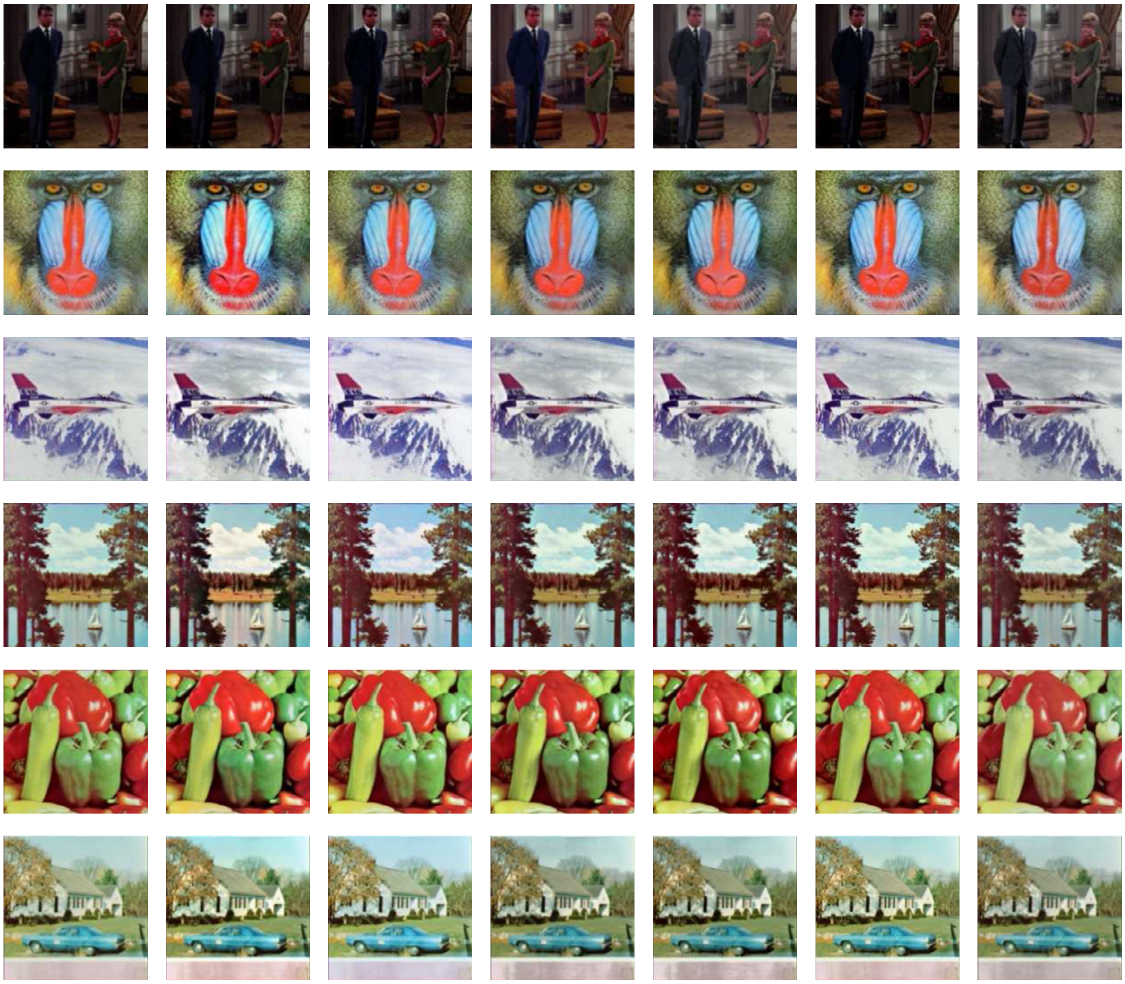
The experiments are conducted on two colorful image databases, which include Kodak [31] and SIPI [32]. The Kodak and SIPI are two famous colorful natural image databases.

4.1. Visual comparisons

The colorful natural images often have rich color information, and the hue and saturation of different images are usually different. A high quality enhanced colorful image needs to own high level of detail visibility and contrast. Meanwhile, there must be less visible distortion, which can be called color distortion and detail distortion, in the enhanced image. For color distortion problem, the hue of enhanced image should be same as that of original image, and for detail distortion problem, the pixels in image should be distributed reasonably.

From the general view, it can be easily observed from Fig. 6 and Fig. 7 that the five methods achieve different contrast enhancement results. For better presentation of image details, some areas in these images are enlarged and the locations for those partial enlarged screenshots are shown in Fig. 8. In Fig. 9, the partial enlarged screenshots for six images in Fig. 8 are presented as examples to show the problems of detail visibility, detail distortion and color distortion in ABPCERDH, CERDHMM, LCECRDH, RCEC and RDHBPCE.

From the point of view of detail visibility, the proposed method has the highest level of detail visibility compared to four other methods. It can be observed from the screenshots in the first row in Fig. 9 that the grasses have the clearest details by using the proposed method. Also, from the screenshots in the fourth and



(a) Original (b) ABPCERDH (c) CERDHMM (d) LCECRDH (e) RCEC (f) RDHBPCE (g) Proposed

Fig. 7. Comparisons of enhanced images on SIPI.

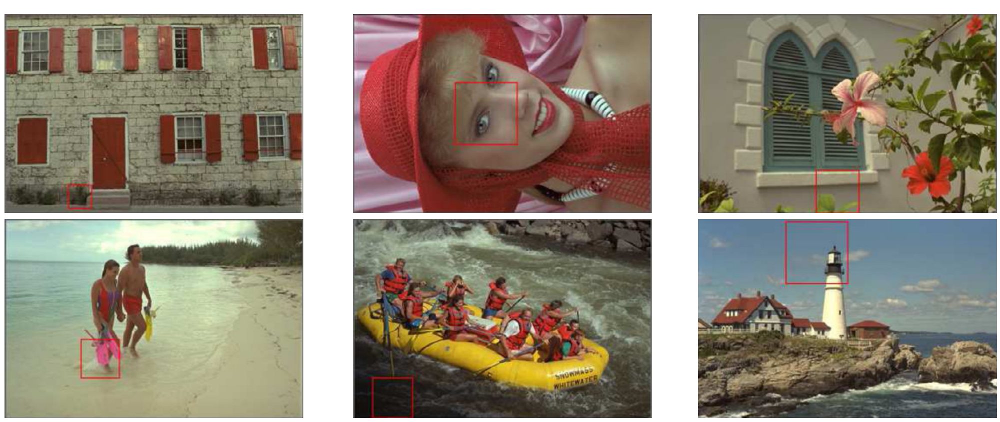


Fig. 8. The comparative locations of partial enlarged screenshots for six original images in Fig. 6.

fifth rows in Fig. 9, the details of white waves are clearer in the proposed screenshots. However, the white waves in other images are not clear enough. For example, in the second and third images in the fourth and fifth rows in Fig. 9, the hue of white waves is changed and color distortion is introduced, in the fourth and fifth images in the fourth and fifth rows in Fig. 9, the details of white waves are hard to observe. That is because ABPCERDH and CERDHMM enhance image contrast on R, G and B channels, respectively. LCECRDH and RCEC do not maintain the histogram distribution of original image. For RDHBPCE, the contrast enhanced results have poor detail visibility. By contrast, the proposed method maintains the histogram distribution of original image by mapping operation in preprocessing, and these areas are clearer after data hiding.

From the point of view of detail distortion, this problem often occurs along with the problem of poor detail visibility. From the fourth and fifth images in the second, third and sixth rows in Fig. 9, the area of woman face, the area of wall and the area of sky

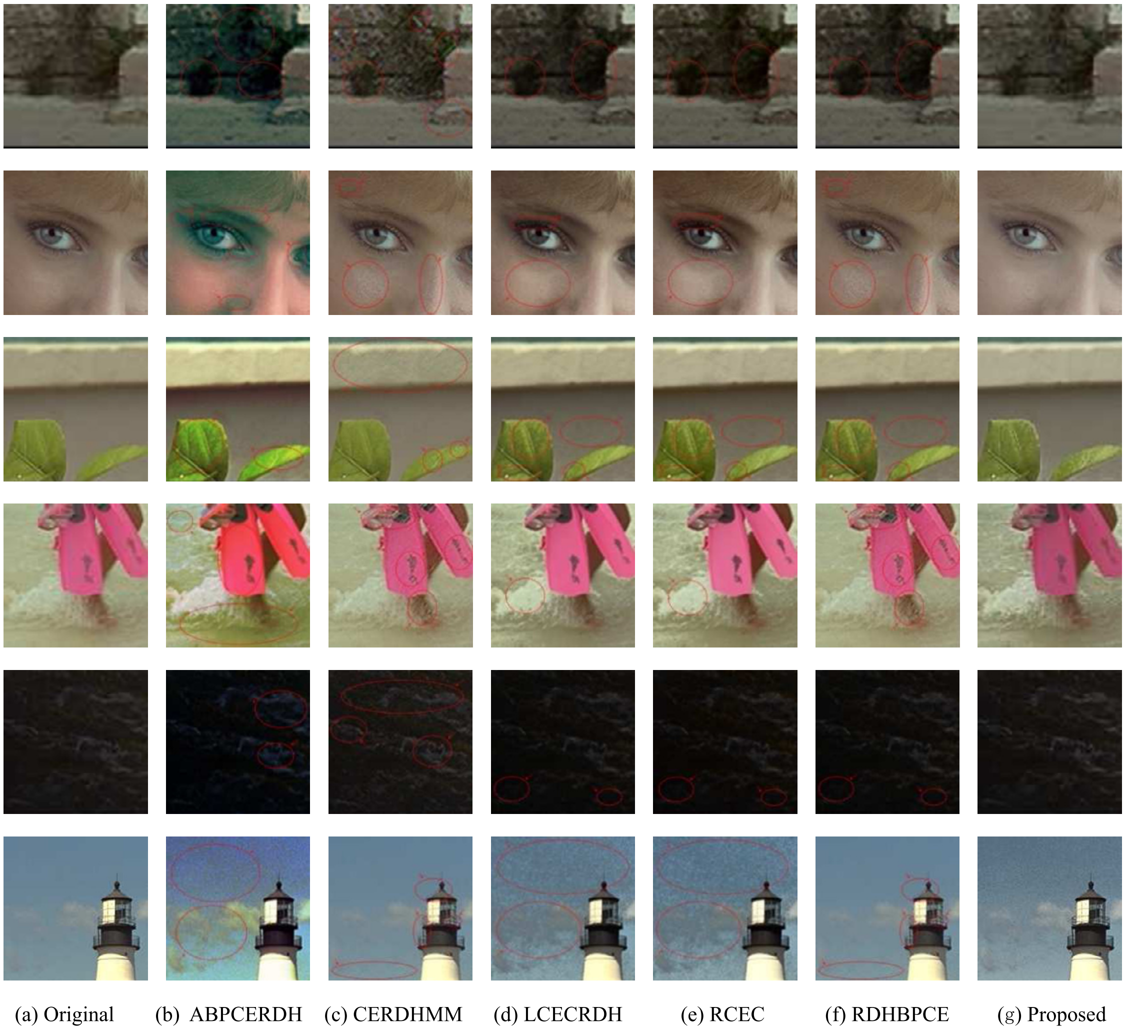


Fig. 9. Comparisons of partial enlarged screenshots for Fig. 8.

all have obvious disordered pixels by using LCECRDH and RCEC. By contrast, there is no detail distortion in the last column in Fig. 9, because the pixels are reasonably distributed in enhanced images by using the proposed method.

Finally, from the most important point of view of color distortion, the hue of enhanced image should be same as that of original image. If the hue of enhanced image changes, then it means the color of the original image is modified, which is not allowed in colorful image enhancement. The comparison of whether the hue of original image is preserved is presented in Fig. 9. Because ABPCERDH and CERDHMM directly enhance the R, G and B channels, the hue of each pixel is not carefully processed. As a result, the second and third columns in Fig. 9 have obvious color distortion, where ABPCERDH results in large area of color distortion and CERDHMM results in some pixels with color distortion. By contrast, the proposed method enhances image contrast based on hue preservation. So there is no color distortion in the proposed enhanced images.

As a conclusion, the proposed method is able to enhance the contrast of colorful natural images without color distortion and detail distortion compared to four other up-to-date methods. In addition, the detail visibility is also better than others.

4.2. Statistical analysis

We use several metrics to objectively measure the performance of different methods in this section. The metrics include PSNR, SSIM, MOS and CIEDE2000, in which CIEDE2000 is the primary metric for color images [27] and others are auxiliary metrics. PSNR and SSIM are two metrics which are usually used to measure the image quality. In the domain of image enhancement, MOS and CIEDE2000 are famous for measuring the quality of enhanced image. Firstly, we invited different people to subjectively score the enhanced images, and their average score is represented by the MOS [15]. Then, CIEDE2000 [33] is defined by the International Commission on Illumination and used to examine the color difference between two color images. A high CIEDE2000 value means a large color difference between the original image and the enhanced image.

The performance measurements of five methods are presented in Table 5, Table 6 and Table 7. Empty bins for embedding secret information are represented by parameter pairs in this experiment, which indicate the number of empty bins to be emptied by different methods. The pairs used in Table 5, Table 6 and Table 7 are 10, 20 and 30, respectively. In the tables, the number with bold font indicates the best result of corresponding metric.

The larger PSNR and SSIM values mean better image quality, the proposed method achieves the best results on two databases when 10 pairs are used for embedding, and the second best results are achieved when 20 pairs and 30 pairs are used for embedding. Similar to PSNR, the proposed method basically acquires the largest SSIM values in three tables. The results of PSNR and SSIM prove

Table 5
Performance measurements of four methods on Kodak and SIPI (10 pairs).

Metric	Database	ABPCERDH	CERDHMM	LCECRDH	RCEC	RDHBPCE	Proposed
PSNR	Kodak	28.1072	27.6276	31.0451	29.8828	31.2319	**32.7914**
	SIPI	29.8895	25.9337	30.6452	28.9052	30.2322	**31.7360**
SSIM	Kodak	0.8964	0.8511	0.9719	0.9650	0.9613	**0.9789**
	SIPI	0.9242	0.8311	**0.9589**	0.9400	0.9486	0.9565
MOS	Kodak	80	82	85	86	88	**92**
	SIPI	80	82	85	85	86	**90**
CIEDE2000	Kodak	7.9753	4.5230	2.3881	2.5117	4.3571	**2.0117**
	SIPI	5.8471	6.9066	2.5014	2.7095	4.2307	**2.3200**

Table 6
Performance measurements of four methods on Kodak and SIPI (20 pairs).

Metric	Database	ABPCERDH	CERDHMM	LCECRDH	RCEC	RDHBPCE	Proposed
PSNR	Kodak	**28.8864**	27.6276	25.9257	24.6111	27.8372	27.4312
	SIPI	**29.7421**	25.9337	25.4658	23.7913	28.0735	26.4677
SSIM	Kodak	0.8978	0.8511	0.9348	0.9150	0.9448	**0.9497**
	SIPI	0.9235	0.8311	0.9098	0.8722	**0.9493**	0.9101
MOS	Kodak	79	82	86	86	87	**90**
	SIPI	80	82	85	86	88	**90**
CIEDE2000	Kodak	7.3848	4.5230	4.1184	4.5551	4.8351	**3.7120**
	SIPI	5.8766	6.9066	4.6388	5.1313	5.8964	**4.4683**

Table 7
Performance measurements of four methods on Kodak and SIPI (30 pairs).

Metric	Database	ABPCERDH	CERDHMM	LCECRDH	RCEC	RDHBPCE	Proposed
PSNR	Kodak	**28.7620**	27.6276	23.0887	22.0716	26.4432	24.3252
	SIPI	**29.7341**	25.9337	22.8613	21.3657	27.8322	23.7352
SSIM	Kodak	0.8997	0.8511	0.8967	0.8793	**0.9275**	0.9208
	SIPI	**0.9231**	0.8311	0.8690	0.8181	0.8826	0.8602
MOS	Kodak	75	82	85	85	86	**90**
	SIPI	75	82	84	85	87	**88**
CIEDE2000	Kodak	7.8186	4.5230	5.5696	6.1057	4.4683	**4.3468**
	SIPI	6.9331	6.9066	6.4686	7.1105	7.2916	**6.3539**

that the qualities of enhanced images using the proposed method are better than those using other methods.

CIEDE2000 is introduced as the most famous metric for measuring color difference of color images, 0 indicates that there is no color difference between the original image and the enhanced image. It is easy to observe that the proposed method always achieves the smallest CIEDE2000 values in the above tables. It indicates that the enhanced images using the proposed methods have little color difference compared with original images. However, the enhanced images using ABPCERDH and CERDHMM achieve larger CIEDE2000 values, and it leads to obvious color distortion. Compared with LCECRDH RCEC, and RDHBPCE, the proposed method still outperforms them from this point of view.

The color distortion and detail distortion problems can be directly observed by human eyes. Therefore, the MOS values reflect the intuitive feeling of different people. The MOS results in Table 5, Table 6 and Table 7 demonstrate that the ABPCERDH and CERDHMM introduce huge color distortion that can be clearly seen, which is presented in the second and third columns in Fig. 9. Meanwhile, the LCECRDH, RCEC, and RDHBPCE introduce less color distortion compared with ABPCERDH method, but the detail distortion which is presented in the fourth and fifth columns in Fig. 9 is still visible. Finally, the proposed method causes no visible distortion compared with four other methods.

The comparisons of different methods are listed in Table 8. The reason that ABPCERDH and CERDHMM introduce huge color distortion is that they process R, G and B channels respectively. As a result, the hue of each pixel is not preserved. However, LCECRDH and RCEC preserve hue according to the HSV color space, and the proposed method preserves hue by using constant hue plane. Furthermore, the problem of detail distortion is solved by the preprocessing in the proposed method, because the proposed preprocessing maintains the distribution of the histogram.

Table 8
Comparisons of different methods.

	ABPCERDH	CERDHMM	LCECRDH	RCEC	RDHBPCE	Proposed
Color distortion	Yes	Yes	**No**	**No**	**No**	**No**
Detail visibility	Poor	Poor	Poor	Poor	Poor	**Good**
Detail distortion	Yes	Yes	Yes	Yes	Yes	**No**

The reason that ABPCERDH and CERDHMM introduce huge color distortion is that they process R, G and B channels respectively. As a result, the hue of each pixel is not preserved. However, LCECRDH and RCEC preserve hue according to the HSV color space, and the proposed method preserves hue by using constant hue plane. Furthermore, the problem of detail distortion is solved by the preprocessing in the proposed method, because the proposed preprocessing maintains the distribution of the histogram.

4.3. Complexity analysis

Suppose that there are totally M pixels in the original image and histogram modification is iteratively performed by N times. For the proposed scheme, the computational complexity is $O(MN)$. Similarly, the computational complexity of [23–26] and [29] are $O(MN)$, because every pixel needs to be scanned.

5. Conclusion

In this paper, a new preprocessing method is proposed to ensure that the enhanced image has no visual distortion. In addition, a hue preservation operation based on constant hue plane is applied to the RDH to ensure that the hue is kept without color distortion, and only the middle channel is operated to ensure better visual quality. The experimental results show that compared with the state-of-the-art methods, the proposed method has better performance in terms of color distortion and detail distortion. In the future, we will further improve the hue preservation method to upgrade the visual quality of enhanced image.

CRediT authorship contribution statement

Guangyong Gao: Conceptualization, Methodology, Resources. **Tingting Han:** Data curation, Formal analysis, Software, Writing – original draft. **Bin Wu:** Funding acquisition, Project administration. **Jiaxin Fu:** Investigation, Visualization, Writing – original draft. **Zhihua Xia:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grant 61662039, Grant U1936118 and Grant 62262033, in part by the Jiangxi Key Natural Science Foundation under Grant 20192ACBL20031, in part by Open Foundation of Henan Key Laboratory of Cyberspace Situation Awareness under Grant HNTS2022033, in part by the Startup Foundation for Introducing Talent of Nanjing University of Information Science and Technology (NUIST) under Grant 2019r070, and in part by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD) fund, and in part by Graduate Scientific Research Innovation Program of Jiangsu Province under Grant KYCX20_0973 and Grant SJCX210369, and in part by the Science and Technology Research Project of Jiangxi Education Department under Grant GJJ211815.

Appendix A

A.1. The proof of equation (2)

Given $\{x, x+1\} \in [0, 255]$ and they are integers, $0 < S \le 50$ and S is integer, and $M_S(x) = M_S(x+1)$. In order to make the mapping results of x and $x+1$ different, the x and $x+1$ will be modified as $x-1$ and x or $x+1$ and $x+2$ according to Eq. (2) in the proposed method. So we need to prove that the $M_S(x-1) \ne M_S(x)$ and $M_S(x+1) \ne M_S(x+2)$.

Firstly, the $M_S(x)$ and $M_S(x+1)$ is calculated according to Eq. (1) with

$$M_S(x) = round\left[\frac{x}{255} \times (255 - S \times 2) + S\right]$$

$$M_S(x+1) = round\left[\frac{x+1}{255} \times (255 - S \times 2) + S\right]$$

$$= round\left[\frac{x}{255} \times (255 - S \times 2) + S + \frac{1}{255} \times (255 - S \times 2)\right]$$

and $M_S(x) = M_S(x+1)$.

Secondly, $M_S(x-1)$ is calculated according to Eq. (1) with

$$M_S(x-1) = round\left[\frac{x-1}{255} \times (255 - S \times 2) + S\right]$$

$$= round\left[\frac{x}{255} \times (255 - S \times 2) + S - \frac{1}{255} \times (255 - S \times 2)\right]$$

Because $M_S(x) = M_S(x+1)$, in order to prove that $M_S(x-1) \ne M_S(x)$, we can prove that $M_S(x-1) \ne M_S(x+1)$.

For two different number a and b, if $|a-b| \ge 1$, then $round(a) \ne round(b)$. Here, let

$$u = \frac{x}{255} \times (255 - S \times 2) + S + \frac{1}{255} \times (255 - S \times 2)$$

$$t = \frac{x}{255} \times (255 - S \times 2) + S - \frac{1}{255} \times (255 - S \times 2)$$

Then, $|u-t|$ is calculated as

$$|u-t| = \left|\frac{2}{255} \times (255 - S \times 2)\right|$$

According to $0 < S \le 50$, then the range of $|u-t|$ is calculated as

$$\left|\frac{2}{255} \times (255 - 50 \times 2)\right| \le |u-t| < \left|\frac{2}{255} \times (255 - 0 \times 2)\right|$$

$$1 < \frac{310}{255} \le |u-t| < \frac{510}{255}$$

It is concluded that $|u-t| > 1$, so $round(u) \ne round(t)$. As a result, it is easy to deduce that $M_S(x-1) \ne M_S(x+1)$. Thus, $M_S(x-1) \ne M_S(x)$ can be deduced. Similarly, $M_S(x+1) \ne M_S(x+2)$ can also be deduced.

References

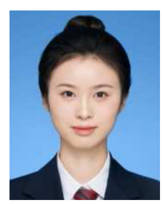
[1] A.K. Singh, Data hiding: current trends, innovation and potential challenges, ACM Trans. Multimed. Comput. Commun. Appl. 16 (2020) 1–16.
[2] Z. Ni, Y.-Q. Shi, N. Ansari, W. Su, Reversible data hiding, IEEE Trans. Circuits Syst. Video Technol. 16 (2006) 354–362.
[3] F.S. Hassan, A. Gutub, Novel embedding secrecy within images utilizing an improved interpolation-based reversible data hiding scheme, J. King Saud Univ, Comput. Inf. Sci. (2020).
[4] W. Wang, A reversible data hiding algorithm based on bidirectional difference expansion, Multimed. Tools Appl. 79 (2020) 5965–5988.
[5] H. Yao, F. Mao, Z. Tang, C. Qin, High-fidelity dual-image reversible data hiding via prediction-error shift, Signal Process. 170 (2020) 107447.
[6] M. Xiao, X. Li, Y. Zhao, B. Ma, G. Guo, A novel reversible data hiding scheme based on pixel-residual histogram, ACM Trans. Multimed. Comput. Commun. Appl. (2022).
[7] H.-T. Wu, J.-L. Dugelay, Y.-Q. Shi, Reversible image data hiding with contrast enhancement, IEEE Signal Process. Lett. 22 (2014) 81–85.
[8] G. Gao, Y.-Q. Shi, Reversible data hiding using controlled contrast enhancement and integer wavelet transform, IEEE Signal Process. Lett. 22 (2015) 2078–2082.
[9] H. Chen, J. Ni, W. Hong, T.-S. Chen, Reversible data hiding with contrast enhancement using adaptive histogram shifting and pixel value ordering, Signal Process. Image Commun. 46 (2016) 1–16.
[10] S. Kim, R. Lussi, X. Qu, H.J. Kim, Automatic contrast enhancement using reversible data hiding, in: 2015 IEEE International Workshop on Information Forensics and Security (WIFS), IEEE, 2015, pp. 1–5.
[11] S. Yang, Saliency-based image contrast enhancement with reversible data hiding, in: ICASSP 2020-2020 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE, 2020, pp. 2847–2851.
[12] H. Chen, J. Yuan, W. Hong, J. Ni, T.-S. Chen, On performance improvement of reversible data hiding with contrast enhancement, Comput. J. 63 (2020) 1584–1596.
[13] G. Gao, X. Wan, S. Yao, Z. Cui, C. Zhou, X. Sun, Reversible data hiding with contrast enhancement and tamper localization for medical images, Inf. Sci. 385 (2017) 250–265.
[14] Y. Yang, W. Zhang, D. Liang, N. Yu, A ROI-based high capacity reversible data hiding scheme with contrast enhancement for medical images, Multimed. Tools Appl. 77 (2018) 18043–18065.
[15] G. Gao, S. Tong, Z. Xia, B. Wu, L. Xu, Z. Zhao, Reversible data hiding with automatic contrast enhancement for medical images, Signal Process. 178 (2021) 107817.

[16] S. Namasudra, R. Chakraborty, A. Majumder, N.R. Moparthi, Securing multimedia by using DNA-based encryption in the cloud computing environment, ACM Trans. Multimed. Comput. Commun. Appl. 16 (2020) 1–19.
[17] Y. Yang, X. Xiao, X. Cai, W. Zhang, A secure and privacy-preserving technique based on contrast-enhancement reversible data hiding and plaintext encryption for medical images, IEEE Signal Process. Lett. 27 (2020) 256–260.
[18] Y. Yang, X. Xiao, X. Cai, W. Zhang, A secure and high visual-quality framework for medical images by contrast-enhancement reversible data hiding and homomorphic encryption, IEEE Access 7 (2019) 96900–96911.
[19] M. Veluchamy, B. Subramani, Fuzzy dissimilarity color histogram equalization for contrast enhancement and color correction, Appl. Soft Comput. 89 (2020) 106077.
[20] R. Kumar, A.K. Bhandari, Fuzzified contrast enhancement for nearly invisible images, IEEE Trans. Circuits Syst. Video Technol. 32 (2021) 2802–2813.
[21] W. Zhang, X. Pan, X. Xie, L. Li, Z. Wang, C. Han, Color correction and adaptive contrast enhancement for underwater image enhancement, Comput. Electr. Eng. 91 (2021) 106981.
[22] Y. Ueda, H. Misawa, T. Koga, N. Suetake, E. Uchino, Hue-preserving color contrast enhancement method without gamut problem by using histogram specification, in: 2018 25th IEEE International Conference on Image Processing (ICIP), IEEE, 2018, pp. 1123–1127.
[23] S. Kim, R. Lussi, X. Qu, F. Huang, H.J. Kim, Reversible data hiding with automatic brightness preserving contrast enhancement, IEEE Trans. Circuits Syst. Video Technol. 29 (2018) 2271–2284.
[24] T. Zhang, T. Hou, S. Weng, F. Zou, H. Zhang, C. Chang, Adaptive reversible data hiding with contrast enhancement based on multi-histogram modification, IEEE Trans. Circuits Syst. Video Technol. (2022), https://doi.org/10.1109/TCSVT.2022.3146159.
[25] H.-T. Wu, Y. Wu, Z. Guan, Y.-m. Cheung, Lossless contrast enhancement of color images with reversible data hiding, Entropy 21 (2019) 910.
[26] Z. Guan, H.-T. Wu, A reversible contrast enhancement scheme for color images, in: 2020 IEEE International Conference on Multimedia and Expo (ICME), IEEE, 2020, pp. 1–6.
[27] Y. Yang, T. Zou, G. Huang, W. Zhang, A high visual quality color image reversible data hiding scheme based on BRG embedding principle and CIEDE2000 assessment metric, IEEE Trans. Circuits Syst. Video Technol. 32 (2021) 1860–1874.
[28] W. Chen, Y.Q. Shi, G. Xuan, Identifying computer graphics using HSV color model and statistical moments of characteristic functions, in: 2007 IEEE International Conference on Multimedia and Expo, IEEE, 2007, pp. 1123–1126.
[29] H.-T. Wu, X. Cao, R. Jia, Y.-M. Cheung, Reversible data hiding with brightness preserving contrast enhancement by two-dimensional histogram modification, IEEE Trans. Circuits Syst. Video Technol. 32 (11) (Nov. 2022) 7605–7617, https://doi.org/10.1109/TCSVT.2022.3180007.
[30] H.-T. Wu, S. Tang, J. Huang, Y.-Q. Shi, A novel reversible data hiding method with image contrast enhancement, Signal Process. Image Commun. 62 (2018) 64–73.
[31] The Kodak Lossless True Color Image Suite, Kodak, http://r0k.us/graphics/kodak/.
[32] The Signal and Image Processing Institute, SIPI, https://sipi.usc.edu/database/.
[33] G. Sharma, W. Wu, E.N. Dalal, The CIEDE2000 color-difference formula: implementation notes, supplementary test data, and mathematical observations, Color Res. Appl. 30 (2005) 21–30, Endorsed by Inter-Society Color Council, the Colour Group (Great Britain), Canadian Society for Color, Color Science Association of Japan, Dutch Society for the Study of Color, the Swedish Colour Centre Foundation, Colour Society of Australia, Centre Français de la Couleur.

Guangyong Gao received the Ph.D. Degree from Nanjing University of Posts and Telecommunications, Nanjing, China, in 2012. He is currently a professor with the School of Computer Science, Nanjing University of Information Science and Technology. His research interests include reversible data hiding, computer networks security, multimedia information security, and digital image processing.

Tingting Han received her BS degree in internet of things engineering from Bohai University in 2020, China. She is currently pursuing her MS degree in computer science and technology at the College of Computer and Software, in Nanjing University of Information Science & Technology, China. Her research interests include digital watermark based on WSNs.

Bin Wu received the Ph.D. degree from the Huazhong University of Science and Technology in 2017. He is currently a Lecturer with the School of Computer and Big Data Science, Jiujiang University. His research interests include privacy preserving, big data security, cloud security, information security, and information query.



Jiaxin Fu received his BS degree in computer science and Jingjiang College of Jiangsu University in 2020, China. She is currently pursuing his MS degree in computer science and technology at the College of Computer and Software, in Nanjing University of Information Science & Technology, China. Her research interests include robust steganography based on deep learning.

Zhihua Xia (Member, IEEE) received the B.S. degree in 2006 and the Ph.D. degree in computer science and technology from Hunan University, Yiyang, China, in 2011. He is currently a Professor with the School of Information Science and Technology, Jinan University, Tianhe 510632, China. His research interests include digital forensic and encrypted image processing.