Reversible Data Hiding with Contrast Enhancement Based on Laplacian Image Sharpening

Chengkai Yang[1], Zhihong Li[1], Wenxia Cai[2], Shaowei Weng[3], Li Liu[1], and Anhong Wang[1]
(Corresponding author: Zhihong Li)

Institute of Electronic Information Engineering, Taiyuan University of Science and Technology[1]
Taiyuan 030024, China
College of Mechatronics, Shijiazhuang University, Shijiazhuang, China[2]
School of Information Engineering, Guangdong University of Technology, Guangzhou, China [3]
(Email: zy_lzh@sohu.com)

(Received Oct. 17, 2019; Revised and Accepted Jan. 15, 2020; First Online Feb. 5, 2020)

Abstract

In 2014, Wu *et al.* proposed a reversible data hiding method with contrast enhancement (RDH-CE) that emphasized that the visual quality of the image was more important than having a high peak signal-to-noise ratio (PSNR). But this method focused only on global enhancements and ignored the details. There were more obvious distortions of the visual image as the embedding level increased, and embedding capacity was relatively low when the embedding level was small. Therefore, in this paper, we proposed a new RDH method with contrast enhancement based on Laplacian sharpening. First, the details of the edges of images and the clarity of images were emphasized by Laplacian sharpening, and the visual distortions of the images were reduced by sharpening scale factor. Then, the embedding capacity was increased by combining the difference expansion and digital inverse transformation to apply the operator to all of the pixels in the image. The experimental results demonstrate the effectiveness of the proposed scheme.

Keywords: Reversible data hiding; Laplacian sharpening; Contrast enhancement

1 Introduction

Data hiding has been used extensively in protecting ownership, fingerprinting, authentication and secret communication [9,17,20]. Data hiding can be classified into two categories, *i.e.*, reversible and irreversible data hiding, with the latter usually causing permanent distortion of the image. However, for sensitive images, such as art, military, and medical images as carriers of stored data, permanent damage to the original images is not allowed during the embedding and extraction of information. For example, a patient's record and diagnosis can be embedded into her or his CT image for confidentiality purposes. When a new diagnosis is to be made based on the original image, the hidden data have to be extracted, and the original image has to be recovered losslessly. This requires reversible data hiding (RDH) technology that can both extract the embedded bits and restore the original cover image without any error [1,2,4,7,8,10,12,13,15].

RDH algorithms are based mainly on three techniques, *i.e.*, difference expansion (DE) [1,2,7,12,15], histogram shifting (HS) [4,8,10,13,14], and prediction-error (PE) [5,11,18,19], the purposes of which are to provide higher capacity and PSNR. Tian [12] was the first to propose the idea of DE for RDH. The algorithm computed the features of consecutive pixel pairs in the image using a decorrelation operator, and, then, the data were embedded into an expanded version of these features, thereby effectively improving the hiding capacity. However, RDH based on DE usually causes visual distortion in the stego-image when the difference is large. Ni *et al.* [10] proposed the RDH algorithm based on HS. After determining the peak and zero of the bins of the histogram, this algorithm moved the bins between the peak and the zero toward the zero points, and vacated the bins near the peak to embed the information. Although Ni *et al.* is algorithm achieved a significant improvement in the quality of images and ensured higher PSNR values, the embedding capacity was relatively low due to the limitation on the number of peak points. Ou *et al.* [11] proposed an RDH approach based on PE, in which the pixels were sorted according to pixel correlation, and secret information was embedded according to the difference relationship between the minimum and the second minimum value, as well as the maximum and the second maximum values. The algorithm achieved better image quality, but the hiding capacity was low due to the limited effective difference.

It should be noted that these RDH algorithms pay more attention to the improvement of PSNR than to the visual quality of the stego-image. In 2014, Wu *et al.* [16] proposed a reversible data hiding algorithm with contrast enhancement (RDH-CE), and it provided a new direction for research related to RDH. The motivation for the proposed algorithm was that they believed that the improvement of the contrast in an image was more important than maintaining a high PSNR. Although the value of the PSNR is not high in some images, the improvement of the contrast in the image still can maintain the good visual quality of the image. Therefore, stego-images with better contrast are less likely to be suspicious to attacker when they don't know the original cover image. In order to embed information and improve contrast, Wu *et al.* [16] designed an algorithm based on traditional histogram equalization. Their algorithm pushes the pixel values to the two ends of the dynamic range by hiding data to enhance the contrast of the image. However, this algorithm focuses on the global contrast of the image, and it ignores the local contrast and the details of texture. The algorithm does not achieve higher embedding capacity for the histogram distributions that have lower peaks and wider dynamic ranges, and obvious visual distortion of the image appears when the embedding level is high.

In view of the loss of the details of the texture and the low capacity caused by the traditional RDH-CE scheme, we considered that sharpening the image could enhance the details of the image effectively, such as the edges and the textures of the image, while simultaneously increasing the number of bits embedded in all of the pixels. Therefore, we propose an RDH-CE algorithm based on Laplacian sharpening, which can effectively improve the edges and clarity of images, while increasing their embedding capacities. First, the Laplacian response of all of the pixels is calculated according to the Laplacian operator, and, then, the response and secret bits are mixed with the original pixels in order to enhance the visual effects of the image and hide the secret information. The experimental results showed that the algorithm has higher embedding capacity and image sharpening.

The rest of the paper is organized as follows. In the next section, we review the RDH algorithm and the Laplacian operator which are related closely to the proposed algorithm. In Section 3, we introduce the embedding and extraction processes used in the proposed algorithm. In Section 4, we discuss our evaluation of the performance of the proposed algorithm, our conclusions are presented in Section 5.

2 Related Works

2.1 Wu *et al.*'s Scheme

The RDH-CE algorithm proposed by Wu *et al.* [16] is considered to be the first RDH algorithm to improve image contrast. The algorithm embeds data by changing the distribution of image histograms, and it achieves global enhancement of image contrast. For a grayscale image I, the embedding of data bits starts by searching for the two largest peaks in the histogram of the image. If we assume that I_R represents the peak with a larger pixel value and I_S represents the peak with a smaller pixel value, the bit B_k is embedded into the original image by modifying the pixels values i using Equation (1):

$$i' = \begin{cases} i-1, & if \quad i < I_S \\ I_S - B_k, & if \quad i = I_S \\ i, & if \quad I_S < i < I_R \\ I_R + B_k, & if \quad i = I_R \\ i+1, & if \quad i > I_R \end{cases} \tag{1}$$

This implies that the pixel values between I_S and I_R are unchanged, and the histogram bins outside the peak and the second peak shift one pixel toward both ends of the dynamic range, and the bins next to the peak and the second peak are used to embed the information. This scheme identifies the peak and the second peak repeatedly, and then it shifts the bins and embeds information to fill the dynamic range of the histogram. In fact, the effect of pushing pixel values toward the two extremes of the dynamic range is similar to histogram equalization for improving the global contrast of the image. Thus, it is expected to enhance the global contrast of the image.

Pre-processing is required in this scheme to avoiding pixel overflow. The pixel value i is increased by L when $i \in (0, L-1)$, and decreased by L when $i \in (256-L, 255)$, where L is the number of loops of the algorithm, which is determined by the size of the embedded data. The positions of the pixels during pre-processing are recorded using a location map, and the position where the pixel is changed is recorded as 1, and the position where the pixel is unchanged is recorded as 0. Then, the location map is encoded and compressed as extra bits embedded in the image. During this process, the peak and the second peak must be embedded into the image to ensure the extraction of secret bits and the restoration of the image. In the extraction and recovery process, only I_S and I_R are required.

Since only I_S and I_R are required and they can be extracted by the LSB of the image, the embedded bit $B_k^{'}$ is extracted by considering the values of$I_S$and $I_S - 1$ and I_R and $I_R + 1$ in the stego-image, such that

$$B_k^{'} = \begin{cases} 1, & if \quad i' = I_S - 1 \, or \, i' = I_R + 1 \\ 0, & if \quad i' = I_S \, or \, i' = I_R \end{cases} \tag{2}$$

The original pixel values, i, are recovered using

$$i = \begin{cases} i'+1, & if \quad i' \le I_S - 1 \\ I_S, & if \quad i' = I_S \\ I_R, & if \quad i' = I_R \\ i'-1, & if \quad i' \geqslant I_R + 1 \end{cases} \tag{3}$$

This algorithm can improve the image contrast and embed significant payloads into the stego-image. However, the enhancement that is achieved in the contrast is global enhancement.

2.2 Image Sharpening of Laplace

The Laplace operator is one of the commonly used edge detection and image sharpening operators, and it is described by Equation (4):

$$\begin{aligned}\nabla^2 f(i,j) =& f(i+1,j) + f(i-1,j) + f(i,j+1)\\ &+ f(i,j-1) - 4f(i,j),\end{aligned} \tag{4}$$

where $f(i,j)$ is the pixel value of the digital image, and the Laplace operator also can be represented as a template, as shown in Figure 1.

0	1	0
1	-4	1
0	1	0

(a)

1	1	1
1	-8	1
1	1	1

(b)

0	-1	0
-1	4	-1
0	-1	0

-1	-1	-1
-1	8	-1
-1	-1	-1

(c)

Figure 1: Laplace template, (a) Laplace algorithm template; (b) Laplace extension template; (c) Laplace other templates

The sharpening of the image enhances the grayscale contrast of the image by differential operation, and it highlights the details of the image, which makes a blurred image clearer. The Laplace operator also is a differential operator, and it can enhance the region where the image grayscale is interrupted. Therefore, the Laplace operator is selected to perform template convolution on the image, and the Laplace response image that is generated is superimposed on the original image to generate a sharpened image. The basic method is represented by Equation (5):

$$g(i,j) = f(i,j) + k \nabla^2 f(i,j), \tag{5}$$

where $g(i,j)$ is the pixel value of the sharpened image. It can highlight the image edge while preserving its background.

3 Proposed Scheme

The main intention of our scheme is to absorb the visual effect of the image brought about by sharpening the image, thereby enhancing the detailed information of the image and achieving the purpose of RDH. Therefore, by combining Laplace sharpening, difference expansion and digital inverse transformation, we propose a reversible data hiding algorithm with contrast enhancement based on Laplace sharpening.

Figure 2 shows the framework of the algorithm, which consists of two phases. In the embedding phase, three steps are performed, *i.e.*, global image enhancement, Laplace sharpening and data embedding, and extra bits embedding. In the extraction phase, the order of the three steps is reversed to restore the original cover image and the embedded data. The details of these phases are presented in the following subsections.

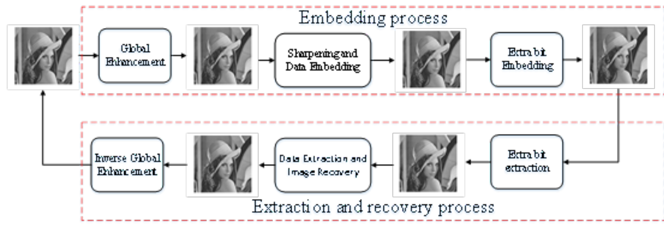

Figure 2: Framework of algorithm

3.1 The Embedding Phase

3.1.1 Pre-Processing of the Image to Achieve Global Enhancement

The embedding process starts with pre-processing the image. For natural pixels of the image that are not distributed over the entire dynamic range, a simple linear stretch is used to achieve global enhancement.

Assuming that H_G, L_G and M_G are the highest, lowest, and average values of the pixel values in an 8-bit $M \times N$ grayscale cover image, I, the pixel value in cover image I are classified first into two groups based on M_G, and the pixel values p in the range $[L_G, M_G - 1]$ are mapped to the range $[0, M_G - 1]$ by using the following transformation function:

$$F_L(p) = \left\lfloor \frac{M_G - 1}{M_G - 1 - L_G}(p - L_G) \right\rfloor \tag{6}$$

Similarly, the pixel values, p, in the range $[M_G, H_G]$ are mapped to the range $[M_G, 255]$ by using the following function:

$$F_H(p) = \lfloor \frac{255 - M_G}{H_G - M_G}(p - M_G) + M_G \rfloor. \tag{7}$$

Because the transformation functions in Equations (6) and (7) strictly are monotonically increasing functions, the two functions are connected seamlessly. Thus, stretching the intensity values using these functions preserves the order of the intensities without any merging between neighboring intensities. However, in order to ensure that the image can be recovered completely after the secret information has been extracted, the parameters of the transformation function must be embedded into the cover image as additional information.

3.1.2 Laplace Sharpening and Data Embedding

The next stage is sharpening and embedding secret data in the globally enhanced image. The following Laplace

0	-1	0
-1	4	-1
0	-1	0

Figure 3: Laplace operator

operator was chosen to ensure higher embedding capacity and reversibility of the algorithm. The processes of Laplace sharpening and embedding data are described as follows:

Input: The pre-processed cover-image, $I^{'}$, sized 512×512, and the randomly generated secret bits, B_k.

Output: The stego-image, LW.

Step 1. As shown in Figure 4, divide the cover-image, $I^{'}$, into region A and region B for embedding the secret bits and unchanging area, respectively, and each small square represents a pixel. For example, given a 512×512 cover image,region A contains 510×510 pixels, and the pixels in the first row and column on the far side of the image, *i.e.*, region B, are not processed.

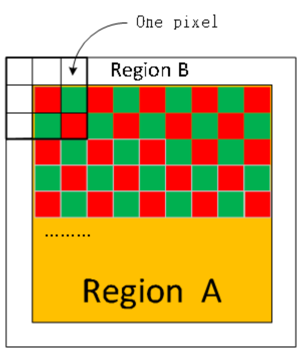

Figure 4: Division of the cover image region

Step 2. Select a 3×3 block from the first pixel of the cover image Region A, as shown in the red area of Figure 4, and perform a Laplace convolution on the block center pixel value (red region), to get the Laplace response of the center pixel $\bigtriangledown^2 f(i,j)$.

$$\begin{aligned}\bigtriangledown^2 f(i,j) =& 4f(i,j) - f(i+1,j) - f(i-1,j) \\ & - f(i,j+1) - f(i,j-1).\end{aligned} \quad (8)$$

Step 3. Sum the current image pixel and the Laplace response of the point according to Equation (9) to obtain a response pixel, $P(i,j)$.

$$P(i,j) = f(i,j) + \left[\frac{1}{k} \times \bigtriangledown^2 f(i,j)\right], \quad (9)$$

where k is the degree of scaling of the Laplace response. The value of k is determined by the pixel value of the image detail that must be enhanced, as well as the visual effect.

Step 4. Embed the secret bits into the response pixel according to Equation (10) and obtain the watermark sharpening pixel, LW.

$$LW(i,j) = \begin{cases} P(i,j) + 1 + B_k, & if \quad P(i,j)\, mod2 = 1 \\ P(i,j) + B_k, & if \quad P(i,j)\, mod2 = 0 \end{cases} \quad (10)$$

where B_k is the sequence of the secret information.

Step 5. Repeat Steps 2 through 4 until all of the blocks have been scanned.

Step 6. Perfect the remaining pixels (green areas) of region A according to the same operation on the sharpened image LW of the above steps to further adjust the image contrast. The selection of the k-value also depends on the scaling required and the visual effect of the image.

3.1.3 Embedding Extra Information

In the aforementioned process, if the result of the pixels exceeds 255 or is less than 0, we must consider the pixel overflow, and the pixel that may overflow is not processed and retains the original value. As shown in Equation (11), the location map (LM) is used to record the position of the pixel. The location map requires code compression for extra information to be embedded into the image.

$$LM(i,j) = \begin{cases} 1, & if \quad LW(i,j) < 0 \ or \ LW(i,j) > 255 \\ 0, & \qquad others \end{cases} \quad (11)$$

In this paper, the two parts of extra information, *i.e.*, the parameters of the transformation function and LM, are embedded by pixel value ordering and the prediction error expansion embedding scheme (PVO-k) [11]. This is because the algorithm effectively can embed additional information into the image without affecting the enhanced image. The PVO-k algorithm is not described here, because the embedding of extra bits can be replaced by any RDH algorithm.

3.2 Data Extraction and Image Restoration

The goal of data extraction is to extract the secret bits from the stego-image accurately while ensuring that the cover image is not distorted. In our scheme, the data extraction algorithm is a simple inverse process of data embedding. Its steps are described as follows:

Input: The stego-image LW.

Output: The cover-image, I, and the secret bits, B_k.

Step 1. Extract the extra bit through the inverse process of PVO-k. And obtain the location map and the parameters of the linear transformation function.

Step 2. Divide the stego-image into region A and region B; extraction is started from the green area pixels of region A in Figure 4.

Step 3. The embedded information is extracted according to Equation (12).

$$B_k{}' = LSB\left(LW\left(i,j\right)\right). \tag{12}$$

Step 4. Restore the response pixels using the acquired embedded information, as shown in Equation (13).

$$P' = \left(LW\left(i,j\right) - B_k{}'\right). \tag{13}$$

Step 5. Restore the pixels,$I'(i,j)$,of the point according to Equation (14).

$$\begin{aligned} I'(i,j) = & \lfloor \frac{1}{k+4} \times [k \times P' + LW(i+1,j) \\ & + LW(i-1,j) + LW(i,j+1) \\ & + LW(i,j-1)] \rfloor . \end{aligned} \tag{14}$$

Step 6. The cover image I can be restored completely according to the linear transformation parameters.

3.3 An Example Demonstrating the Process

In this section, we present a simple example of processing the hypothetical image shown in Figures 5 and 6 in order to show the mechanics of the proposed algorithm. In order to guarantee reversibility, the white pixels in the image are not processed.

Start with the first shaded pixel 26, and bring the template into the template using its top, bottom, left, and right values, here the value of k is 2.

Embedding process:

$$\begin{aligned} \nabla^2 f(1,1) &= \lceil \frac{4\times 26 - 22 - 25 - 24 - 22}{2} \rceil = 6 \\ P(1,1) &= 26 + 6 = 32 \\ B_k &= 1 \\ LW\left(1,1\right) &= 32 + 1 = 33 \end{aligned}$$

Extraction process:

$$\begin{aligned} B_k{}' &= 1 \\ P' &= 33 - 1 = 32 \\ I'\left(i,j\right) &= \left\lfloor \frac{1}{2+4} \times \left(2\times 32 + 22 + 25 + 24 + 22\right) \right\rfloor \\ &= 26. \end{aligned}$$

Red is the hidden pixel of the first layer, and green is the hidden pixel of the second layer. Together they form Region A, and the embedding process is started from the red pixels, and all red pixels are completed before the green pixels. In the extraction, starting from the green pixels, the least significant bits are extracted sequentially, and the original values are restored using Equations (13) and (14); then, the secret bits and the original pixels are extracted and restored according to the restored green pixels until all secret information has been extracted and the original image has been restored.

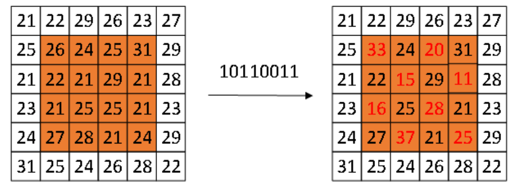

Figure 5: The first layer

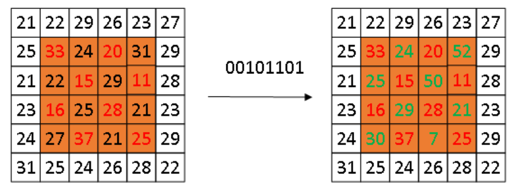

Figure 6: The second layer

4 Experimental Results

The proposed algorithm was compared with the traditional contrast enhancement algorithm proposed by Wu *et al.* [16], the SARDH algorithm proposed by Jafar *et al.* [6] and the PAB algorithm proposed by Chen *et al.* [3]. In the comparison, the SARDH algorithm here also was an RDH algorithm that considered image sharpening. The test images were 512×512 grayscale images of Lena, Baboon, Airplane, and Watch, and they were used to verify the effectiveness of the proposed algorithm.

Figure 7 shows a shadow at the nose of the (b) and (c) images, and the nose of the (d) image is not smooth enough. Figure(e) has better visual effects than the other three figures.

In Figure 8, although the hair in images(b) and (c) is relatively darker in color and the global contrast is strong enough, it is more abrupt in terms of visual effects. Compared with the other three figures, the overall visual effect of image(e) is gentler, and the details of the hair are clearer.

Compared to the other three pictures, the letters on the airplane in Figure 9 are clearer than the letters in image(e). The mountains and clouds in images (b) and (c) are too abrupt, and the details of the mountains and clouds details are clearer in image(d).

Compared to the other three pictures, the picture of the digit on the watch and the buckle in Figure 10 is clearer than that of image(e). As can be seen from the partial detail in Figures 7, 8, 9, and 10, the proposed algorithm can enhance the details at the edges of the image better, and the visual effect of the image is not too abrupt

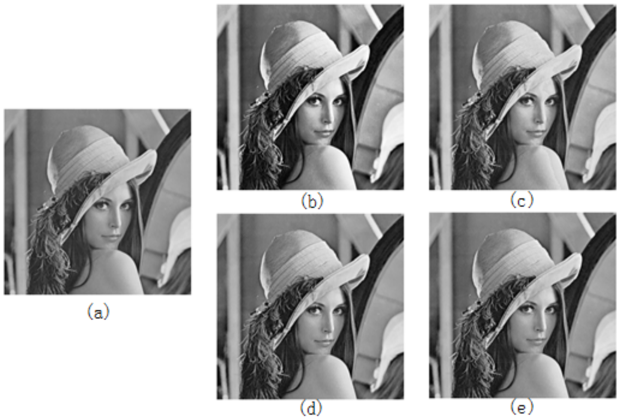

Figure 7: (a) original, (b) RDH-CE, (c) PAB, (d) SARDH, (e) the proposed scheme

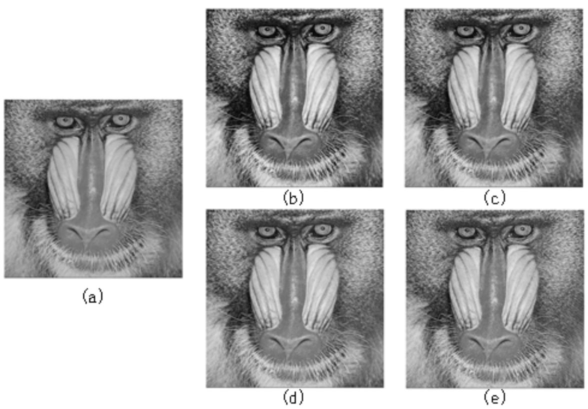

Figure 8: (a) original, (b) RDH-CE, (c) PAB, (d) SARDH, (e) the proposed scheme

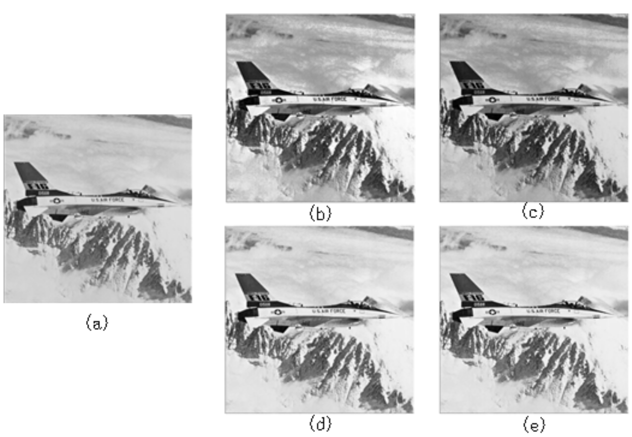

Figure 9: (a) original, (b) RDH-CE, (c) PAB, (d) SARDH, (e) the proposed scheme

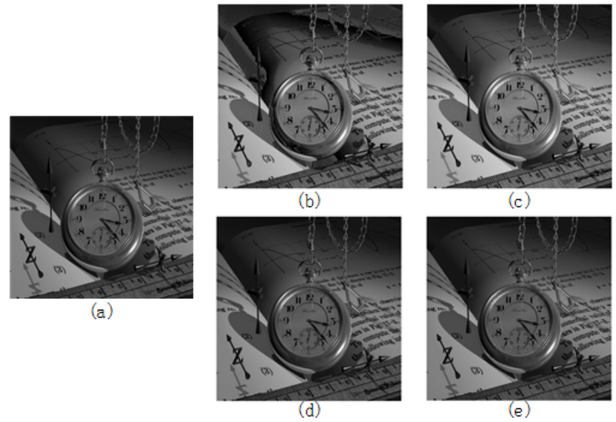

Figure 10: (a) original, (b) RDH-CE, (c) PAB, (d) SARDH, (e) the proposed scheme

after the overall enhancement, making it more consistent with the human visual sense.

Based on the description of the above four experiments, the RDH-CE and PAB schemes mainly improved the global contrast of the images, and the proposed scheme did a better job of enhancing the details at the edges of the images. Thus, the visual effect of the image will not be too abrupt after the overall enhancement, and the image is more consistent with the human visual sense. Thus, the proposed scheme makes up for the shortcoming associated with the enhancement of the details in the images.

In order to evaluate the performance of the proposed scheme further and compare it with the state-of-the-art algorithms, different performance metrics were considered. The gray mean grads (GMG), information entropy (H) and tenegrad measure (TEN) were used to judge the enhancement effect of the images, and the embedding capacity (E) was used to measure the data hiding performance.

1) The gray mean grads (GMG). The GMG value is obtained by squaring the gray value of adjacent pixels in the length and width directions of the image and then determining the root mean square, which can reflect the contrast and texture features of the image. Higher GMG values usually reflect higher clarity and quality in images. The formula used to calculate GMG was:

$$GMG = \frac{1}{(M-1)(N-1)} \sum_{i=1}^{M-1} \sum_{j=1}^{N-1} \sqrt{\frac{\Delta I_x^2 + \Delta I_y^2}{2}} \tag{15}$$

Table 1 shows the GMG values of different algorithms. Compared with the other three algorithms, the proposed scheme achieves some enhancement of the details for all pixels of the image, and the gradient value of each pixel is relatively higher. So the proposed scheme has better visual effects concerning the details of the image.

2) Information entropy (H). Information entropy, H,

Table 1: Gray Mean Grads (GMG) of different algorithms

Image	RDH-CE	PAB	SARDH	Proposed
Lena	6.9029	6.4713	8.7163	14.1713
Baboon	24.8951	22.6067	25.9783	57.8684
Airplane	7.7471	7.3489	8.9676	14.2437
Watch	8.7406	8.7406	8.9476	15.9453

represents the average amount of information in an image. Higher H values usually reflect more details in the image. The formula is:

$$H = -\sum_{i=0}^{l-1} p(i) \, log_2 p(i) \, . \tag{16}$$

The data in Table 2 indicate that the H value of the proposed scheme is slightly higher than the H values for other algorithms, which indicates that our proposed algorithm provides more details.

3) The tenegrad measure (TEN). The TEN is a well-known benchmark measure of the sharpness of images, and it is defined by Equation (17). Higher TEN values usually reflect higher contrast levels and stronger edges in images.

$$TEN = \sum_{i} \sum_{j} G_{ij}. \tag{17}$$

It is obvious that our algorithm has better performance than the others.

4) The embedding capacity (E). The E is reported as the pure embedding capacity that is normalized by the image size to measure the embedding rate in bits per pixel (bpp) using Equation (18).

$$E = \frac{Embedded\,Bits - Extra\,bit}{M \times N}. \tag{18}$$

The results show that the proposed algorithm significantly improves the number of embedding bits. Compared with the SARDH algorithm, our algorithm provides an embedding capacity closer to 1 bpp, which is far more than the other three algorithms.

5 Conclusion

The RDH-CE scheme, which improves the contrast in images after information has been embedded, gives a new direction for RDH. It can be said that the stego-images that have better contrast are less likely to attract the attention of attackers if they do not know the original image. In this paper, we proposed an RDH-CE algorithm based on image sharpening, which can sharpen the details of images and embed a large amount of secret information. Compared with the traditional, contrast-enhanced RDH algorithm, the proposed algorithm compensates for the details of images that are neglected by the global enhancement. Our experimental results indicated that our proposed algorithm provided better visual effects for the details of images than the other algorithm. Also, our experimental evaluations verified that the proposed algorithm has a large embedding capacity and a relatively better edge enhancement effect.

Acknowledgments

This study was supported by the Shanxi Natural Science Foundation under Grand (No.201801D121129), National Natural Science Foundation of China (No.61672373, No.61501315), Scientifc and Technological Innovation Team of Shanxi Province (No.201705D131025), Key Innovation Team of Shanxi 1331 Project (2017015), Collaborative Innovation Center of Internet+3D Printing in Shanxi Province(201708). The authors gratefully acknowledge the anonymous reviewers for their valuable comments.

References

[1] C. C. Chang, Y. H. Huang, and T. C. Lu, "A difference expansion based reversible information hiding scheme with high stego image visual quality," *Multimedia Tools and Applications*, vol. 76, no. 10, pp. 12659–12681, 2017.

[2] C. C. Chen, Y. H. Tsai, and H. C. Yeh, "Difference-expansion based reversible and visible image watermarking scheme," *Multimedia Tools and Applications*, vol. 76, no. 6, pp. 8497–8516, 2017.

[3] H. Chen, J. Ni, W. Hong, and T. S. Chen, "Reversible data hiding with contrast enhancement using adaptive histogram shifting and pixel value ordering," *Signal Processing: Image Communication*, vol. 46, pp. 1–16, 2016.

[4] G. Coatrieux, W. Pan, N. Cuppens-Boulahia, F. Cuppens, and C. Roux, "Reversible watermarking based on invariant image classification and dynamic histogram shifting," *IEEE Transactions on Information Forensics and Security*, vol. 8, no. 1, pp. 111–120, 2013.

[5] W. He, K. Zhou, J. Cai, L. Wang, and G. Xiong, "Reversible data hiding using multi-pass pixel value ordering and prediction-error expansion," *Journal of*

Table 2: Image information entropy (H) of different algorithms

Image	RDH-CE	PAB	SARDH	Proposed
Lena	7.6231	7.589	7.6459	7.7157
Baboon	7.5601	7.5077	7.6941	7.8814
Airplane	7.1881	7.081	6.9508	7.2376
Watch	7.2642	7.341	7.164	7.3724

Table 3: Tenegrad measure (TEN) of different algorithms ($\times 10^7$)

Image	RDH-CE	PAB	SARDH	Proposed
Lena	1.5086	1.3944	1.6493	1.8695
Baboon	3.8919	3.506	3.9346	5.213
Airplane	1.7147	1.6234	1.8091	2.0154
Watch	1.6651	1.5682	1.7645	1.9008

Table 4: Actual embedding capacity (E) of different algorithms)

Image	RDH-CE	PAB	SARDH	Proposed
Lena	0.2108	0.2217	0.5803	0.9822
Baboon	0.2078	0.1715	0.2863	0.9038
Airplane	0.4795	0.4439	0.6218	0.9788
Watch	0.258	0.2658	0.6847	0.9537

Visual Communication and Image Representation, vol. 49, pp. 351–360, 2017.

[6] I. F. Jafar, K. A. Darabkh, and R. R. Saifan, "Sardh: A novel sharpening-aware reversible data hiding algorithm," *Journal of Visual Communication and Image Representation*, vol. 39, pp. 239–252, 2016.

[7] S. Lakshmanan and M. Rani, "Reversible data hiding in medical images using edge detection and difference expansion technique," *Journal of Computational and Theoretical Nanoscience*, vol. 15, no. 6-7, pp. 2400–2404, 2018.

[8] L. Liu, C. C. Chang, and A. Wang, "Reversible data hiding scheme based on histogram shifting of n-bits planes," *Multimedia Tools and Applications*, vol. 75, no. 18, pp. 11311–11326, 2016.

[9] L. Liu, C. C. Chang, and A. Wang, "Data hiding based on extended turtle shell matrix construction method," *Multimedia Tools and Applications*, vol. 76, no. 10, pp. 12233–12250, 2017.

[10] Z. Ni, Y. Q. Shi, N. Ansari, and W. Su, "Reversible data hiding," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 16, no. 3, pp. 354–362, 2006.

[11] B. Ou, X. Li, Y. Zhao, and R. Ni, "Reversible data hiding using invariant pixel-value-ordering and prediction-error expansion," *Signal Processing: Image Communication*, vol. 29, no. 7, pp. 760–772, 2014.

[12] J. Tian, "Reversible data embedding using a difference expansion," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 13, no. 8, pp. 890–896, 2003.

[13] P. H. Vo, T. S. Nguyen, V. T. Huynh, and T. N. Do, "A novel reversible data hiding scheme with two-dimensional histogram shifting mechanism," *Multimedia Tools and Applications*, vol. 77, no. 21, pp. 28777–28797, 2018.

[14] J. Wang, J. Ni, X. Zhang, and Y. Q. Shi, "Rate and distortion optimization for reversible data hiding using multiple histogram shifting," *IEEE Transactions on Cybernetics*, vol. 47, no. 2, pp. 315–326, 2017.

[15] W. Wang, Y. Ye, T. Wang, and W. Wang, "Reversible data hiding scheme based on significant-bit-difference expansion," *IET Image Processing*, vol. 11, no. 11, pp. 1002–1014, 2017.

[16] H. T. Wu, J. L. Dugelay, and Y. Q. Shi, "Reversible image data hiding with contrast enhancement," *IEEE Signal Processing Letters*, vol. 22, no. 1, pp. 81–85, 2014.

[17] B. Xia, A. Wang, C. C. Chang, and L. Liu, "Reversible data hiding for VQ indices using hierarchical state codebook mapping," *Multimedia Tools and Applications*, vol. 77, no. 16, p. 20519–20533, 2018.

[18] S. Yi, Y. Zhou, and Z. Hua, "Reversible data hiding in encrypted images using adaptive block-level prediction-error expansion," *Signal Processing: Image Communication*, vol. 64, pp. 78–88, 2018.

[19] X. Yu, X. Wang, and Q. Pei, "Reversible watermarking based on multi-dimensional prediction-error ex-

pansion," *Multimedia Tools and Applications*, vol. 77, no. 14, pp. 18085–18104, 2018.

[20] Y. Wang, J. Shen, and M. Hwang, "A survey of reversible data hiding for VQ-compressed images," *International Journal of Network Security*, vol. 20, no. 1, pp. 1–8, 2018.

Biography

Chengkai Yang was born in Yuncheng City, Shanxi Province on June 19, 1995. In July 2016, he graduated from the Department of Electronic Information Engineering, Taiyuan University of Science and Technology with a Bachelor of Engineering degree. Now, he is a graduate student in Taiyuan University of Science and Technology. His research direction is reversible data hiding.

Zhihong Li was born in Shanxi Province, P. R. China in 1970. He received the M.E. degree in the Electronic Information Engineering, Taiyuan University of Science and Technology in 1997. His research interest includes image/video coding and secret image sharing.

Wenxia Cai received her B.S. degree and her M.S. degree from North China Electric Power University (Baoding), China respectively in 2003 and in 2006. She is currently a lecturer in Shijiazhuang University. Her research interests include information processing technology and mechatronics, etc.

Shaowei Weng received her Ph.D. degree from the Institute of Information Science at Beijing Jiaotong University in July 2009. She is currently an associate professor in the School of Information Engineering at Guangdong University of Technology. Her research interests include image processing, data hiding and digital watermarking, pattern recognition, computer vision, etc. Now she is in charge of two NSFC (Natural Science Foundation of China) project. In addition, she participates in 973 and 863 projects as the backbone. She publishes more than 20 papers, and applies two national patents.

Li Liu received her B.E. degree in communication engineering in 2002, from Lanzhou Railway University and M.E. degree in communication and information system in 2006, from Lanzhou Jiaotong University. Now, she is a Ph. D student in Northwestern Polytechnical University. Her current research interests include information hiding and secret sharing.

Anhong Wang was born in Shanxi Province, P. R. China in 1972. She received the Ph. D. degree in the Institute of Information Science, Beijing Jiaotong University in 2009. She is now the director of Institute of Digital Media and Communication, Taiyuan University of Science and Technology. Her research interest includes image/video coding and secret image sharing.