LETTER

Reversible Data Hiding Based on Adaptive Modulation of Statistics Invertibility

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SUMMARY This paper proposes an improved method of reversible data hiding with increased capacity. The conventional method determines whether to embed a data bit in an image block according to the statistics of pixels in that block. Some images have pixel statistics that are inadequate for data hiding, and seldom or never have data embedded in them. The proposed method modulates the statistics invertibility to overcome such disadvantages, and is also able to improve the quality of the image containing the hidden data using block-adaptive modulation. Simulationresults show the effectiveness of the proposed method.

key words: *local property, modulo arithmetic, digital watermarking, medical images*

1. Introduction

Data hiding technology has been studied widely from the perspectives on data security [1], [2] and nonsecure applications [1], [3]. A data hiding method degrades the *original* signal to embed data in it. Many conventional methods extract data from the distorted, or *stego* signal, and leave the distorted signal as is; this is irreversible data hiding. Reversible data hiding methods, however, not only extract hidden data from a stego signal, but also recover the original signal from the stego signal [4]–[7]. This feature is preferable in medical, satellite and military applications.

A reversible data hiding method that embeds data in the spatial domain has been proposed [7]. To guarantee reversibility, this method only embeds data in embeddable pixels that meet certain criteria, and thus does not need to remember the pixel positions that contain data bits. But, this feature reduces the amount of data that can be hidden, i.e., it reduces the capacity.

This paper proposes an advanced reversible data hiding method to improve the capacity. The pixel value is modified according to the distance between the pixel value and the central value of the dynamic pixel value range before the embedding process takes place. This mechanism avoids unnecessary large modifications of the embeddable pixels because one simple modification rule is applied to the entire image. The proposed method improves the capacity.

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2. Conventional Methods and Problem

Section 2.1 discusses the common attributes of conventional method and the conditions for the proposed method, and describes the conventional method algorithm [7]. And then, the problem is described in Sect. 2.2.

2.1 Conventional Method

Figure 1 shows a block diagram of Conventional method [7]. Grayscale image $\mathbf{f}$ of size $X \times Y$, in which each pixel is represented by K bits, i.e., $\mathbf{f} = \left\{ f(x,y) \mid 0 \le f(x,y) \le 2^K - 1, 0 \le x \le X-1, 0 \le y \le Y-1 \right\}$ is the original image. The binary sequence $\mathbf{w} = \left\{ w_n \mid w_n \in \{0,1\}, \ n = 0, 1, \ldots, N-1 \right\}$ is embedded in $\mathbf{f}$ in the spatial domain. The pixel in which one data bit w_n is hidden is the central pixel of a 3×3 block (Fig. 2(a)), g_b ($b = 0, 1, \ldots, B-1$), and the blocks overlap as shown in Fig. 2(b).

This method thus embeds data up to

$$B = \left\lfloor \frac{X-1}{2} \right\rfloor \left\lfloor \frac{Y-1}{2} \right\rfloor \quad \text{[bit]}$$

where $\lfloor p \rfloor$ indicates rounding the real-valued p to the nearest integer towards negative infinity. Parameter B is referred to as the *ideal capacity*, parameter N is the image-dependent *actual capacity*, and $0 \le N \le B$.

Parameter s is used in the decision of whether to hide data in a block. The next section describes algorithm for data embedding, extraction, and restoration of the original

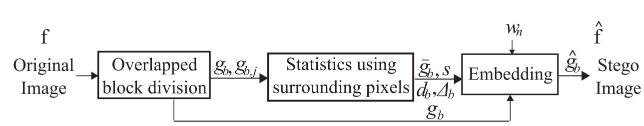
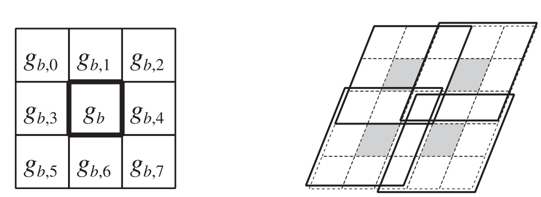


Fig. 1 Conventional reversible data hiding method (Conventional I) [7].



(a) A pixel block. (b) Placement of pixel blocks.

Fig. 2 A pixel block and its placement.

image that uses s throughout.

2.1.1 Derivation of s

Parameter s is used to determine whether to embed data in pixel g_b during the embedding process and whether data is embedded in a certain pixel during the extraction process. Parameter s is the only parameter in this reversible data hiding method.

Step 1 $b := 0$.

Step 2 Calculate the average of the surrounding pixels, $g_{b,j}$ ($j = 0, 1, \ldots, 7$) using Eq. (1). Also calculate the difference between g_b and $\bar{g}_b$.

$$\bar{g}_b = \left\lfloor \frac{1}{8} \sum_{j=0}^{7} g_{b,j} \right\rfloor \tag{1}$$

$$d_b = g_b - \bar{g}_b \tag{2}$$

Step 3 Δ_b is obtained using Eq. (3).

$$\Delta_b = \begin{cases} g_{\max,b} - \bar{g}_b, & d_b \geq 0 \\ g_{\min,b} - \bar{g}_b, & d_b < 0 \end{cases}. \tag{3}$$

$g_{\max,b}$ and $g_{\min,b}$ are the maximum and the minimum of $g_{b,j}$, respectively. That is, $g_{\max,b} = \max_j g_{b,j}$ and $g_{\min,b} = \min_j g_{b,j}$.

Step 4 Parameter s_b, which is a candidate for s, is calculated using

$$s_b = \begin{cases} |\Delta_b|, & \bar{g}_b + 2d_b < 0 \text{ or } 2^K - 2 < \bar{g}_b + 2d_b \\ \infty, & \text{otherwise} \end{cases}. \tag{4}$$

Step 5 $b := b + 1$. If $b < B$, go to Step 2.

Step 6 The minimum of s_b becomes s. That is, $s = \min_b s_b$.

Parameter s is derived using Eqs. (1)–(3) based on the statistics of the pixel value in the original image. The reversibility of the block is considered in Eq. (4).

2.1.2 Embedding

This algorithm uses the parameter s to determine whether to embed data bit w_n in pixel g_b.

Step 1 $b := 0, n := 0$.

Step 2 Using Eq. (5), $\hat{g}_b$, the pixel with hidden data, is derived from embeddable g_b.

$$\hat{g}_b = \begin{cases} \bar{g}_b + 2d_b + w_n, & |\Delta_b| < s \\ g_b, & \text{otherwise} \end{cases}. \tag{5}$$

Step 3 If $|\Delta_b| < s$, $n := n + 1$, $b := b + 1$. If $b < B$, go to Step 2.

Step 4 Stego image $\hat{\mathbf{f}}$ is generated.

This algorithm uses Eq. (5) and parameter s to determine whether g_b is embeddable. Therefore, the capacity N depends on s.

2.1.3 Extraction and Restoration

The extraction and restoration algorithm corresponds to the embedding algorithm above. It is assumed that the parameter s used by the embedding algorithm is already known.

Step 1 $b := 0, n := 0$.

Step 2 Δ_b is obtained using

$$\Delta_b = \begin{cases} g_{\max,b} - \bar{g}_b, & \hat{g}_b - \bar{g}_b \geq 0 \\ g_{\min,b} - \bar{g}_b, & \hat{g}_b - \bar{g}_b < 0 \end{cases}. \tag{6}$$

Step 3 One data bit w_n is extracted by

$$\text{If } |\Delta_b| < s, \quad w_n = (\hat{g}_b - \bar{g}_b) \bmod 2. \tag{7}$$

Step 4 Pixel g_b of the original image is restored using

$$g_b = \begin{cases} \bar{g}_b + \dfrac{\hat{g}_b - \bar{g}_b - w_n}{2}, & |\Delta_b| < s \\ \hat{g}_b, & \text{otherwise} \end{cases}. \tag{8}$$

Step 5 If $|\Delta_b| < s$, $n := n + 1$, $b := b + 1$. If $b < B$, go to Step 2.

Step 6 The N-bit data sequence $\mathbf{w}$ and original image $\mathbf{f}$ are obtained.

The above algorithm is applied to stego image $\hat{\mathbf{f}}$ to extract hidden data $\mathbf{w}$ and restore original image $\mathbf{f}$. In this algorithm, the same parameter s used for the embedding is assumed to be available.

2.2 Problem with the Conventional Method

As shown in Eqs. (4) and (5), when using Conventional algorithm to embed data bit w_b in pixel g_b, invertibility is guaranteed only if Eq. (9) is satisfied.

$$0 \leq \hat{g}_b \leq 2^K - 1. \tag{9}$$

However, there are many pixels g_b that do not satisfy Eq. (9) in an image, and this decreases N significantly. For instance, when $\bar{g}_b = 2^K - 1$ and $\Delta_b = 0$ are blocked, data cannot be embedded in this block or in the entire image.

In the next section presents the solution to this problem.

3. Proposed Method

Figure 3 shows a block diagram of the proposed method,

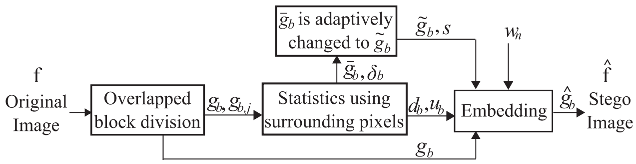


Fig. 3 Proposed method.

an improvement of Conventional method [7], which is capable of embedding only very little or no data at all in some images.

3.1 Proposed Method Algorithm

In the proposed method, $\bar{g}_b$ is substituted adaptively according to the statistics of the pixels $g_{b,j}$ that surround the embedding pixel g_b.

3.1.1 Derivation of s

The proposed method derives parameter s as follows:

Step 1 $b := 0$.

Step 2 The $\bar{g}_b$ and d_b are calculated using Eqs. (1) and (2), and δ_b is calculated by

$$\delta_b = \sqrt{\frac{1}{8}\sum_{j=0}^{7}\left(g_{b,j} - \bar{g}_b\right)^2}. \tag{10}$$

Step 3 u_b is calculated by

$$u_b = g_{\max,b} - g_{\min,b}. \tag{11}$$

Step 4 The s_b is calculated by

$$s_b = \begin{cases} u_b, & \tilde{g}_b + 2d_b < 0 \text{ or } 2^K - 2 < \tilde{g}_b + 2d_b \\ \infty, & \text{otherwise} \end{cases}. \tag{12}$$

where $\tilde{g}_b$ is

$$\tilde{g}_b = \bar{g}_b + 2 \times \text{round}\left((2 + \delta_b)\left(1 - \frac{\bar{g}_b}{2^{K-1}}\right)\right). \tag{13}$$

Step 5 $b := b + 1$. If $b < B$ go to Step 2.

Step 6 The minimum of s_b becomes s.

The proposed method also derives parameter s from the pixel statistics as in conventional method [7]. However, $\bar{g}_b$, d_b and $|\Delta_b|$ in Eq. (4) for conventional method [7] are used instead of the $\tilde{g}_b$ given by Eq. (13), as well as d_b and u_b. This effect is described in Sect. 3.2.

3.1.2 Embedding

The proposed method of embedding takes place in the following steps:

Step 1 $b := 0, n := 0$.

Step 2 The pixel with the hidden data, $\hat{g}_b$, is derived from the embeddable pixel g_b using

$$\hat{g}_b = \begin{cases} \tilde{g}_b + 2d_b + w_n, & u_b < s \\ g_b, & \text{otherwise} \end{cases}. \tag{14}$$

Step 3 If $u_b < s$, $n := n + 1$, $b := b + 1$. If $b < B$, go to Step 2.

Step 4 Stego image $\hat{\mathbf{f}}$ is generated.

The proposed method uses $\tilde{g}_b$ and u_b to derive s as described in Sect. 3.1.1 using $\tilde{g}_b$ and u_b in Eq. (14).

3.1.3 Extraction and Restoration

The proposed method uses the following steps to extracts hidden data and restore original image.

Step 1 $b := 0, n := 0$.

Step 2 u_b is obtained using Eq. (11) as well as the embedding algorithm.

Step 3 One data bit w_n is extracted by

$$\text{If } u_b < s, \quad w_n = (\hat{g}_b - \tilde{g}_b) \bmod 2. \tag{15}$$

Step 4 Pixel g_b of the original image is restored using

$$\bar{g}_b = \begin{cases} \bar{g}_b + \dfrac{\hat{g}_b - \tilde{g}_b - w_n}{2}, & u_b < s \\ \hat{g}_b, & \text{otherwise} \end{cases}. \tag{16}$$

Step 5 If $u_b < s$, $n := n + 1$, $b := b + 1$. If $b < B$, go to Step 2.

Step 6 The N-bit data sequence $\mathbf{w}$ and the original image $\mathbf{f}$ are obtained.

In the proposed method, u_b and $\tilde{g}_b$ are obtained instead of $|\Delta_b|$ and $\bar{g}_b$, using Eqs. (15) and (16).

3.2 Discussions

The proposed method improves the actual capacity.

Firstly, $\bar{g}_b$ is a lower bound of the dynamic range of pixels where Eqs. (17) and (13) are approximately equal to 1. The $\bar{g}_b$ is the upper bound of the dynamic range of pixels where Eq. (17) is approximately equal to −1. Similarly, $\bar{g}_b$ is the center of the dynamic range where Eq. (17) is approximately 0.

$$\left(1 - \frac{\bar{g}_b}{2^{K-1}}\right) \tag{17}$$

Therefore, this term is the key that not only prevents underflow and overflow of $\hat{g}_b$, but also prevents excessive changes in $\bar{g}_b$.

Second, δ_b is the standard deviation of the surrounding pixels. The difference d_b between the embedding pixel g_b and the average of the surrounding pixels $\bar{g}_b$ is also small. Conversely, δ_b and d_b increase in a fluctuating block. The gain of Eq. (17) is adjusted to guarantee reversibility of Eq. (5).

Third, Δ_b is obtained from the sign of d_b in the conventional method, as it corresponds to $\hat{g}_b - \bar{g}_b$ after embedding the data. However, in the proposed method d_b does not correspond to the sign of $\hat{g}_b - \tilde{g}_b$ after data embedding because of the correction expression. Here, it does not depend on the sign by introducing the u_b. The data are not embeded under the block which changes rapidly. Even so, the exchange of algorithms between the conventional and proposed methods is possible because of the use of u_b.

As shown above, $\bar{g}_b$ in the proposed method is adaptively changed to $\tilde{g}_b$ based on the statistics of the pixel values in the pixel block. As a result, $\bar{g}_b$ eliminates limitations on embedding g_b and increases the chance that this embedding will be acceptable.

4. Experimental Results

The proposed method was evaluated with eight-bit grayscale images ($K = 8$) were obtained from an image database [8], [9]. The data to be hidden, **w**, consisted of equiprobable zeros and ones.

The proposed method increases the actual capacity of the image compared to Conventional method [7]. Table 1 compares the performance of Conventional method [7] and the proposed method. Images Aerial6 and Barbara, in particular, show that actual capacity is obviously increased. Figure 5 show the image Barbara, Comparison of the payload for the Conventional method and proposed method by u controlling the payload.

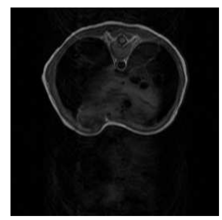
Figure 4 show the performance of the proposed method for four images (Mrchest001, Kodak20, Rular.512, and Texmos3b.p512) for which Conventional method [7] could embed little to no data. Maximum payload is shown in Table 2. Figure 6 show the stego images obtained using the proposed methods for the Mrchest001 and Kodak20 images, in which even one bit of data cannot be embedded by Conventional method [7]. These images the proposed method using adaptive modification generates stego images.

Table 1 Comparison of the capacity for the Conventional method [7] and proposed method for an ideal capacity of $B = 65025$ [bits]. actual capacity, N; embeddable ratio, N/B.

Image	Conventional method [7]			Proposed method		
	N [bits]	N/B [%]	PSNR [dB]	N [bits]	N/B [%]	PSNR [dB]
Aerial6	2622	4.0	65.1	21860	33.6	39.9
Airplane	63474	97.6	40.1	65025	100.0	37.8
Baboon	34548	53.1	38.9	44162	67.9	34.4
Barbara	31573	48.6	47.4	52870	81.3	34.2
Lena	60451	93.0	41.2	65025	100.0	35.5
Peppers	60006	92.3	42.4	64842	99.7	35.9
Sailboat	64444	99.1	36.3	64524	99.2	33.8
Tiffany	59025	90.8	43.3	64985	99.9	35.2

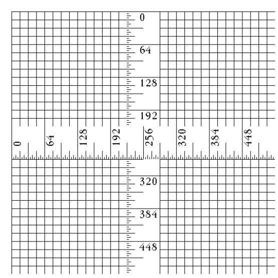
Table 2 Performance of the proposed method.

Image	ideal capacity B [bits]	N [bits]	N/B [%]	PSNR [dB]
Mrchest001	16129	16129	100.0	33.1
Kodak20	97665	81814	83.7	39.2
Ruler.512	65025	39289	60.4	45.4
Texmos3b.p512	65025	1496	2.3	47.6

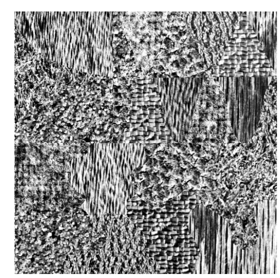


(a) Mrchest001

(b) Kodak20



(c) Ruler.512



(d) Texmos3b.p512

Fig. 4 Images for performance evaluation.

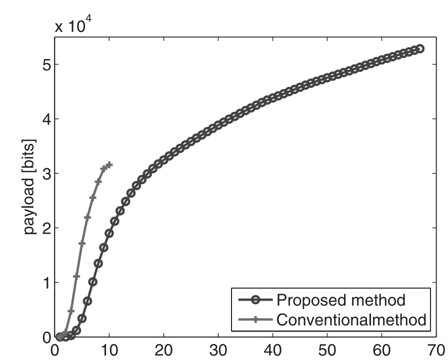
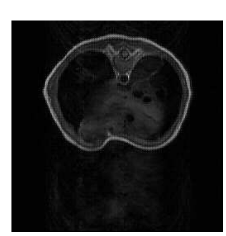


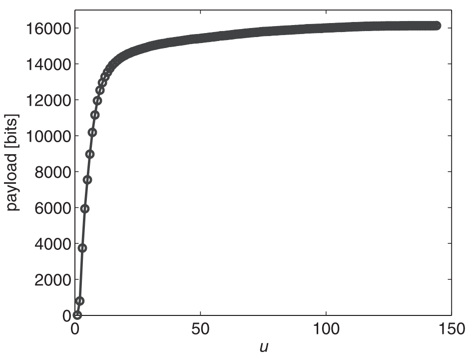
Fig. 5 Comparison of the payload to the conventional and proposed method by u controlling the payload, "Barbara."



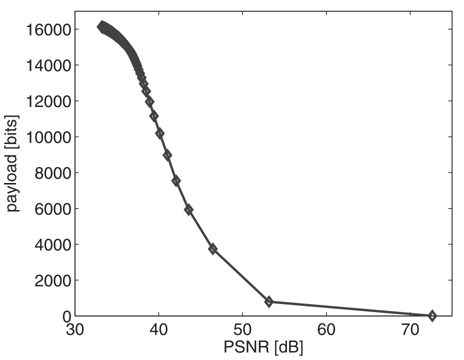
(a) N = 16129 [bits], PSNR = 33.1 [dB].

(b) N = 81814 [bits], PSNR = 39.2 [dB].

Fig. 6 Stego images to the proposed method.



(a) Payload versus *u*.



(b) Payload vs stego image quality.

Fig. 7 Payload and Stego image quality controlled by *u*, "Mrchest001."

In addition, the proposed method can control payload and stego image quality by $0 < u < s$ show in Fig. 7. When parameter s is substituted for u, Fig. 7(a) shows the control of payload by u and Fig. 7(b) shows the PSNR by payload.

5. Conclusions

This paper has proposed an advanced reversible data hiding method for increasing capacity. The proposed method includes adaptive and reversible modification of pixel values, which provides a greater capacity than the Conventional method [7]. Moreover, this method offers controlling the capacity for hidden data and the stego image quality.

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