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Lossless Data Hiding in the Spatial Domain for High Quality Images

Hong Lin JIN[†a)], *Student Member*, Masaaki FUJIYOSHI[††], *and* Hitoshi KIYA[††], *Members*

SUMMARY A lossless data embedding method that inserts data in images in the spatial domain is proposed in this paper. Though a lossless data embedding method once distorts an original image to embed data into the image, the method restores the original image as well as extracts hidden data from the image in which the data are embedded. To guarantee the losslessness of data embedding, all pixel values after embedding must be in the dynamic range of pixels. Because the proposed method modifies some pixels to embed data and leaves other pixels as their original values in the spatial domain, it can easily keep all pixel values after embedding in the dynamic range of pixels. Thus, both the capacity and the image quality of generated images are simultaneously improved. Moreover, the proposed method uses only one parameter based on the statistics of pixel blocks to embed and extract data. By using this parameter, this method does not require any reference images to extract embedded data nor any memorization of the positions of pixels in which data are hidden to extract embedded data. In addition, the proposed method can control the capacity for hidden data and the quality of images conveying hidden data by controlling the only one parameter. Simulation results show the effectiveness of the proposed method; in particular, it offers images with superior image quality to conventional methods.

key words: *information embedding, watermarking, image quality, capacity, payload, data hiding*

1. Introduction

Data embedding technology has been diligently studied, not only for security-related problems [1], [2] — in particular, intellectual property rights protection of digital content [3] — but also non-security-oriented [1], [4] problems, such as broadcast monitoring [5]. Data embedding techniques hide data in a target signal, referred to as the *original* signal. They then generate a slightly distorted signal that is referred to as a *stego* signal. Many data embedding techniques extract but do not remove hidden signals from stego signals. In military and medical applications, restoration of the original signal as well as extraction of the hidden signals are preferred [6]–[8]. For images, *lossless* data embedding techniques that also restore the original image have been proposed [6]–[10]. Lossless data embedding is classified into two groups [6]: one embeds data for restoration as well as data to be hidden [6], [9], [10], while the other only embeds data to be hidden [7], [8].

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[†]The author is with the Graduate School of Engineering, Tokyo Metropolitan University, Hino-shi, 191–0065 Japan.
[††]The authors are with the Faculty of System Design, Tokyo Metropolitan University, Hino-shi, 191–0065 Japan.
a) E-mail: jin@isys.eei.metro-u.ac.jp

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This paper proposes a lossless data embedding method that hides only data to be embedded in the spatial domain. The proposed method embeds and extracts the data by using only one global parameter that is based on the statistics of surrounding pixels of the pixels in which the data are hidden. All pixel values of stego images need to be in the dynamic range of pixels to guarantee the losslessness of data embedding. Because the proposed method modifies some pixels to embed data and leaves other pixels as these original values, it can easily keep all pixel values in the dynamic range. However, conventional methods modifying coefficients in a transformed domain have a hard time guaranteeing the losslessness. It thus results in simultaneous improvement in the amount of hidden data and the quality of a stego image. Moreover, this method is able to extract hidden data without knowledge of the positions of the hidden data. This method can also control the image quality of a stego image and the capacity for hidden data by controlling the only one parameter.

2. Conventional Methods

Generalized diagram of lossless data hiding is shown in Fig. 1. An original image is slightly distorted to convey data, and the distorted images is referred to as a stego image. In lossless data hiding, the original image is recovered from the stego image as well as the hidden data are extracted. Whereas, in most data hiding methods referred to as lossy data hiding methods, data are extracted from a stego image and the stego image is left as it is distorted.

Conventional methods that embed not only data to be hidden but also data for restoration *replace* the original pixel values [6], [9] or transformed coefficients [10], with a new values for hiding data. These methods, thus, cannot restore the original image, and data for restoration also have to be embedded, as shown in Fig. 2.

Other conventional methods that do not have to embed data for restoration (Fig. 3) also have disadvantages. The location of pixels for embedding must be memorized [7].

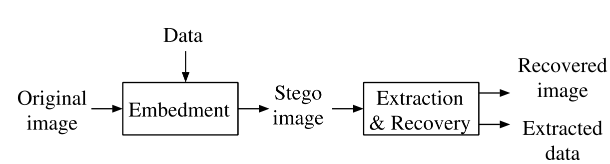


Fig. 1 Generalized lossless data hiding.

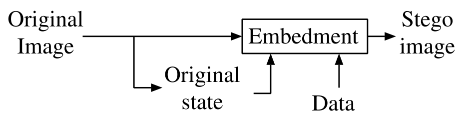


Fig. 2 General diagram of conventional methods embedding the original state information as well as data to be hidden [6], [9], [10].

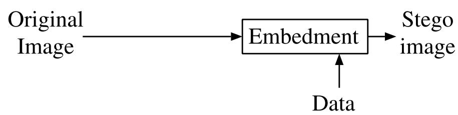


Fig. 3 General diagram of conventional methods embedding only data to be hidden [7], [8].

Two parameters are used and inverse transformation often moves pixel values to the outside of the dynamic range of pixel values [8].

In the next section, a novel lossless data embedding method is proposed that hides data in the spatial domain and does not embed additional data for restoration. Only one parameter is used in the proposed method, in which hidden data and the original image are completely restored from the stego image.

3. Proposed Method

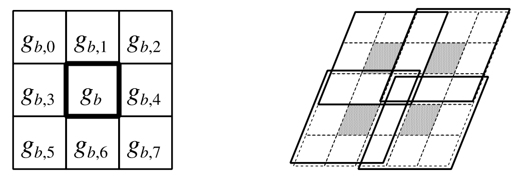
$X \times Y$-sized gray scale image $\mathbf{f}$ in which each pixel is represented by K bits, i.e., $\mathbf{f} = \left\{f(x,y) \,\middle|\, 0 \le f(x,y) \le 2^K - 1, 0 \le x \le X-1, 0 \le y \le Y-1\right\}$, is assumed to be an original image. The proposed method embeds binary sequence $\mathbf{w} = \left\{w_n \,\middle|\, w_n \in \{0,1\}, n = 0, 1, \ldots, N-1\right\}$ 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-sized block, g_b $(b = 0, 1, \ldots, B-1)$, as shown in Fig. 4(a), and blocks are overlapped, as shown in Fig. 4(b). The various size and shape of block and the various placement of blocks are able to be employed and vary the performance of this method [11]. However, since the aim of this paper is the proposal of the whole method, only 3×3-sized square block is employed in this paper for its simplicity.

This method, thus, embeds data up to

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

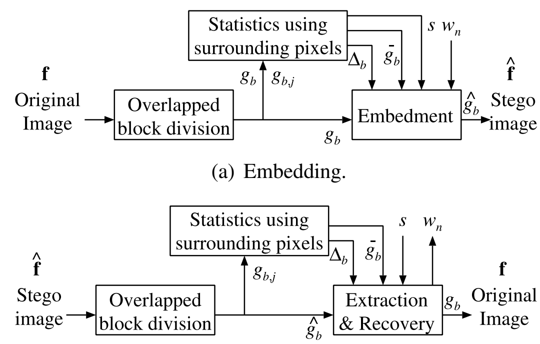
where $\lfloor p \rfloor$ rounds the real-value p to the nearest integer towards negative infinity. Parameter B is referred to as the *ideal capacity*. Whereas, parameter N is the image dependent *actual capacity* and $0 \le N \le B$.

The block diagram of the proposed method is shown in Fig. 5. First, original image $\mathbf{f}$ is divided into 3×3-sized overlapped blocks, and the statistics are derived in each block. One parameter s is obtained according to the statistics. This parameter, s, is an image dependent parameter. In each block, this method determines whether g_b is capable to convey w_n, i.e., *embeddable* or not, based on s, and embeds $\mathbf{w}$ into embeddable g_b's. Finally, the stego image $\hat{\mathbf{f}} = \left\{\hat{f}(x,y) \,\middle|\, 0 \le \hat{f}(x,y) \le 2^K - 1\right\}$ is obtained.



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

Fig. 4 A pixel block and its placement.



(a) Embedding.

(b) Extracting.

Fig. 5 Proposed method.

3.1 Algorithm

Firstly, the proposed method derives parameter s that is one and only one parameter. Then, the method losslessly embeds data to an original image using s. The extraction of hidden data and the restoration of the original image also use parameter s. These three algorithms, i.e., derivation of s, embedding, and extraction and restoration are subsequently described from the next section.

3.1.1 Derivation of s

The algorithm to derive parameter s from original image $\mathbf{f}$ as follows.

1. $b := 0$.
2. The average of the surrounding pixels, $g_{b,j}$ $(j = 0, 1, \ldots, 7)$, is obtained by Eq. (2). The difference between g_b and $\bar{g}_b$ is also derived.

$$\bar{g}_b = \left\lfloor \frac{1}{8} \sum_{j=0}^{7} g_{b,j} \right\rfloor \tag{2}$$

$$d_b = g_b - \bar{g}_b \tag{3}$$

3. Δ_b is obtained by Eq. (4).

$$\Delta_b = \begin{cases} g_{\max,b} - \bar{g}_b, & d_b \ge 0 \\ g_{\min,b} - \bar{g}_b, & d_b < 0 \end{cases}, \tag{4}$$

where $g_{\max,b}$ and $g_{\min,b}$ are the maximum and the minimum of $g_{b,j}$'s, respectively. That is,

$$g_{\max,b} = \max_j g_{b,j} \tag{5}$$

$$g_{\min,b} = \min_j g_{b,j} \tag{6}$$

4. Parameter s_b, which is a candidate of s, is derived by Eq. (7).

$$s_b = \begin{cases} |\Delta_b|, & \bar{g}_b + 2d_b < 0 \quad \text{or} \quad 2^K - 2 < \bar{g}_b + 2d_b \\ \infty, & \text{others} \end{cases}. \tag{7}$$

5. $b := b + 1$. Continue to Step 2 unless $b = B$.
6. The minimum of s_b's becomes s. That is,

$$s = \min_b s_b. \tag{8}$$

3.1.2 Embedding

This algorithm determines whether g_b is embeddable based on parameter s described above. One data bit w_n is hidden in an embeddable g_b.

1. $b := 0, n := 0$.
2. By Eq. (9), $\hat{g}_b$, the pixel with hidden data, is derived from embeddable g_b.

$$\hat{g}_b = \begin{cases} \bar{g}_b + 2d_b + w_n, & |\Delta_b| < s \\ g_b, & \text{others} \end{cases}. \tag{9}$$

3. If $|\Delta_b| < s$, $n := n + 1$.
4. $b := b + 1$. Continue Step 2 until $b = B$.
5. Stego image $\hat{\mathbf{f}}$ is generated.

3.1.3 Extraction and Restoration

The following algorithm is applied to stego image $\hat{\mathbf{f}}$ to extract hidden data $\mathbf{w}$ and restore original image $\mathbf{f}$.

1. $b := 0, n := 0$.
2. Δ_b is obtained by Eq. (10).

$$\Delta_b = \begin{cases} g_{\max,b} - \bar{g}_b, & \hat{g}_b - \bar{g}_b \geq 0 \\ g_{\min,b} - \bar{g}_b, & \hat{g}_b - \bar{g}_b < 0 \end{cases}. \tag{10}$$

3. One data bit w_n is extracted by the following equation, if $|\Delta_b| < s$.

$$w_n = (\hat{g}_b - \bar{g}_b) \bmod 2 \tag{11}$$

4. Pixel g_b of the original image is restored by Eq. (12).

$$g_b = \begin{cases} \frac{\hat{g}_b + \bar{g}_b - w_n}{2}, & |\Delta_b| < s \\ \hat{g}_b, & \text{others} \end{cases}. \tag{12}$$

5. If $|\Delta_b| < s$, $n := n + 1$.
6. $b := b + 1$. Continue to Step 2 unless $b = B$.
7. N-bit data sequence $\mathbf{w}$ and original image $\mathbf{f}$ are obtained.

3.2 Features

3.2.1 Losslessness

The proposed method restores original images as well as extracts hidden data from stego images. To have these properties, the following are required:

- All stego pixels, $\hat{g}_b$'s, are in the dynamic range of pixels.
- Stego pixel $\hat{g}_b$ is completely split into hidden one data bit w_n and original pixel g_b.

The former is represented by

$$0 \leq \hat{g}_b \leq 2^K - 1, \quad \forall b. \tag{13}$$

From Eq. (9) and $w_n \in \{0, 1\}$, Eq. (13) is satisfied by skipping g_b's that satisfy

$$\bar{g}_b + 2d_b > 2^K - 2, \tag{14}$$

or

$$\bar{g}_b + 2d_b < 0, \tag{15}$$

in an embedding process. For g_b that satisfies Eqs. (14) or (15), s_b is set to $|\Delta_b|$ in Eq. (7). Eq. (8) gives s as the minimum s_b, and s is used as the threshold to determine whether g_b is embeddable in Eq. (9). Consequently, this method avoids embedding data in g_b's that satisfy Eqs. (14) or (15), and it is concluded that Eq. (13) is guaranteed.

Splitting a stego pixel into the original pixel and hidden one bit data is achieved as follows. The part for embeddable pixels, i.e., pixels satisfying $|\Delta_b| < s$, of Eq. (9) is transformed into

$$\hat{g}_b = \bar{g}_b + 2\,(g_b - \bar{g}_b) + w_n = 2g_b - \bar{g}_b + w_n, \tag{16}$$

and this results in Eq. (12). In Eq. (12), $\hat{g}_b$ is the stego pixel itself and is known in any extraction process. $\bar{g}_b$ is given by Eq. (2) and is also known in any extraction process. Since surrounding pixels $g_{b,j}$ in a stego image are the same as that in the original image, $\bar{g}_b$ in the original and in stego images are the same. The proposed method, thus, completely separates $\hat{g}_b$ into g_b and w_n if w_n is obtained. The mechanism to extract w_n from $\hat{g}_b$ is described in the next section.

The proposed method, thus, is a lossless data embedding method.

3.2.2 Obliviousness

A data embedding method that requires no reference image, e.g., the original image, to extract hidden data from a stego image is referred to as an *oblivious* method. Moreover, the proposed method has another obliviousness. It requires no knowledge of the positions of embeddable pixels to extract hidden data. It automatically separates pixels in which data are actually hidden from all the g_b's.

The proposed method extracts hidden data without reference images as follows. Eq. (9) is transformed into

$$\hat{g}_b = \bar{g}_b + 2\,(g_b - \bar{g}_b) + w_n = 2g_b - \bar{g}_b + w_n, \qquad (17)$$

thus,

$$w_n = \hat{g}_b + \bar{g}_b - 2g_b. \qquad (18)$$

From Eq. (18), the proposed method seems to require original pixel g_b to extract hidden one data bit w_n from stego pixel $\hat{g}_b$. The proposed method solves this problem by introducing modulo arithmetic. Once again, Eq. (9) is transformed into

$$\hat{g}_b - \bar{g}_b = 2d_b + w_n. \qquad (19)$$

Since $w_n \in \{0, 1\}$,

$$(2d_b + w_n) \bmod 2 = w_n. \qquad (20)$$

Eq. (11), thus, is guaranteed by Eqs. (19) and (20). Consequently, the proposed method is an oblivious method.

The proposed method leaves g_b as is, unless g_b is embeddable, as shown in Eq. (9). That is, the proposed method must know whether stego pixel $\hat{g}_b$ conveys one data bit w_n to extract $\mathbf{w}$ completely. From the embedding algorithm, if $|\Delta_b|$ is less than s, original pixel g_b is determined to be embeddable by Eq. (9). This Δ_b is computable from a stego image; it, however, varies according to d_b, as shown in Eq. (4). This d_b depends on original pixel g_b, as shown in Eq. (3). The proposed method solves this problem as follows. From Eq. (9),

$$\hat{g}_b - \bar{g}_b = \begin{cases} \bar{g}_b + 2d_b + w_n - \bar{g}_b = 2d_b + w_n, & |\Delta_b| < s \\ g_b - \bar{g}_b = d_b, & \text{others} \end{cases}. \qquad (21)$$

Under the conditions that $w_n \in \{0, 1\}$ and d_b is an integer,

$$\begin{cases} 2d_b + w_n \geq 0, & d_b \geq 0 \\ 2d_b + w_n < 0, & d_b < 0 \end{cases}. \qquad (22)$$

From Eqs. (21) and (22),

$$\begin{cases} \hat{g}_b - \bar{g}_b \geq 0, & d_b \geq 0 \\ \hat{g}_b - \bar{g}_b < 0, & d_b < 0 \end{cases}, \qquad (23)$$

and this property of the proposed method is used in Eq. (11) to determine whether $\hat{g}_b$ conveys w_n. Consequently, the proposed method does not have to memorize positions of pixels in which data are hidden.

The proposed method, thus, is an oblivious method in two senses.

4. Experimental Results

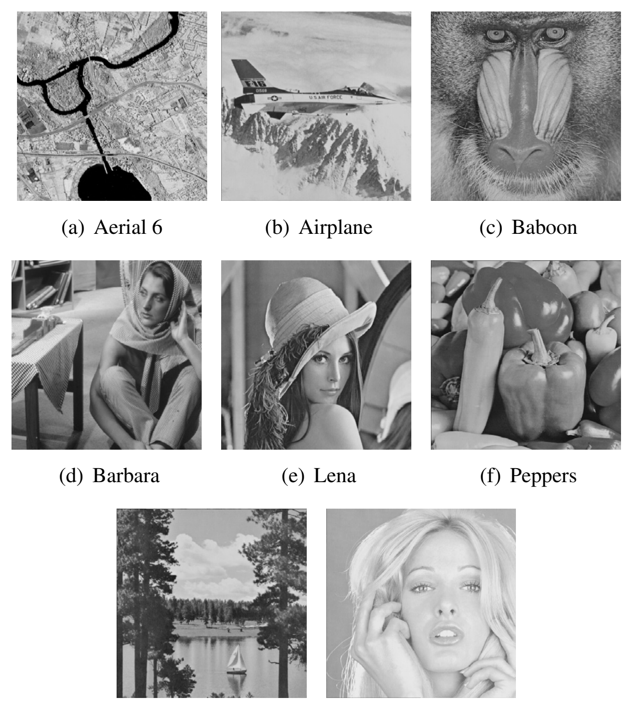
The proposed method is evaluated by using 512×512-sized grayscale images in which each pixel has 256 levels between 0 and 255. That is, $X = Y = 512$, $B = 65025$, and $K = 8$. The images are shown in Fig. 6. Data to be hidden, $\mathbf{w}$, consist of equiprobable zeros and ones. The conditions are summarized in Table 1.

Table 1 Simulation conditions.

Original image **f**	$X = Y = 512$, $K = 8$
Data to be hidden **w**	$w_n \in \{0, 1\}$, equiprobable
Ideal capacity of images	$B = 65025$

Table 2 The actual capacity N [bits], the embeddable ratio N/B [%], the image quality of the stego image in terms of the peak signal-to-noise ratio [dB] when the payload is set as its maximum (N [bits]), and parameter s for embedding N bits data.

Image	N [bits]	N/B [%]	PSNR [dB]	s
Aerial 6	2622	4.0	65.1	1
Airplane	63474	97.6	40.1	54
Baboon	34548	53.1	38.9	23
Barbara	31573	48.6	47.4	10
Lena	60451	93.0	41.2	31
Peppers	60006	92.3	42.4	24
Sailboat	64444	99.1	36.3	67
Tiffany	59025	90.8	43.3	18



(a) Aerial 6 (b) Airplane (c) Baboon
(d) Barbara (e) Lena (f) Peppers
(g) Sailboat (h) Tiffany

Fig. 6 Images for evaluation (from CIPR-RPI [12]).

4.1 Maximum Payload

The actual capacity N [bits], the embeddable ratio N/B [%], the image quality of the stego image in terms of the peak signal-to-noise ratio [dB] when the payload is set as its maximum value (N [bits]), and parameter s for embedding N data bits into evaluated images are shown in Table 2. In the table, the embeddable ratio is greater than 95% for images "Airplane" (Fig. 6(b)) and "Sailboat" (Fig. 6(g)). An example of stego images is shown in Fig. 7. This "Sailboat" conveys 64444 data bits, and the PSNR is 36.3 dB.

By contrast, s for "Aerial 6" (Fig. 6(a)) is quite small;

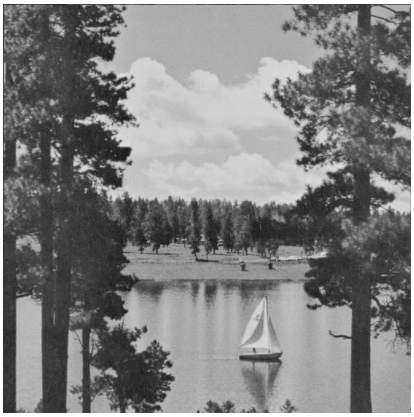
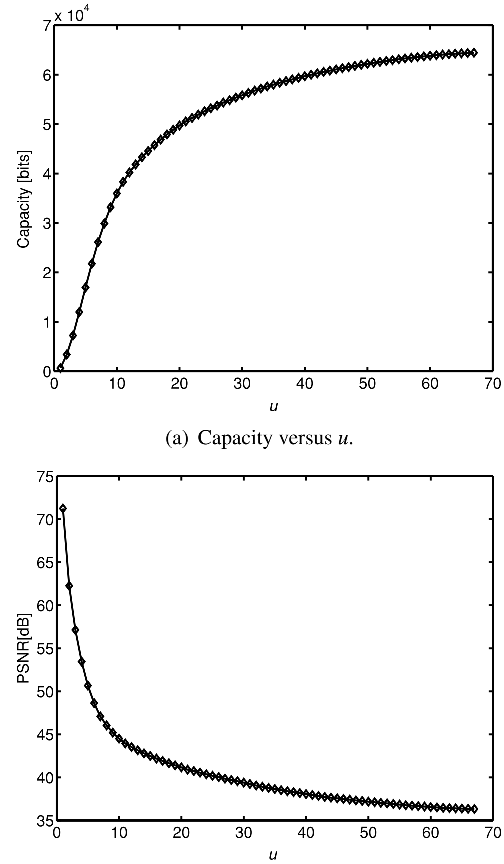


Fig. 7 An example of stego images (Sailboat, PSNR: 36.3 dB).



(a) Capacity versus u.

(b) Image quality versus u.

Fig. 8 Capacity and image quality controlled by u, "Sailboat."

N, is reduced. In "Aerial 6," the avoidance of underflow in the water part where pixel values are quite small makes s quite small. Moreover, the land part where pixel values vary at short distances has few g_b satisfying $|\Delta_b| < s$. Because of these two properties, N is much reduced in "Aerial 6."

4.2 Extension for Controlling Payload and Image Quality

The proposed method can control the capacity for hidden data and the image quality of a stego image by changing s to u, where $0 < u < s$. That is, it uses u rather than s in embedding and extracting processes. Parameter u, then, is the only parameter of the proposed method. Whereas most conventional embedding methods control the capacity by not embedding data in several embeddable components, this skipping requires the memorization of positions of stego components.

The payload of hidden data and the image quality of stego images by using u are shown in Fig. 8. This controllability of the proposed method depends on original images themselves, and versatile control in this method is not easy. This method, however, controls the capacity and the image quality by using only one parameter without memorization of the location of stego pixels. This feature is very useful in practice.

4.3 Performance Comparison

The proposed method is compared to the conventional methods [8]–[10] in terms of the image quality of stego images under the condition that the payload is maximally set to the actual capacity of the conventional methods in each comparison. The results are shown in Table 3. The proposed method chooses adequate u for each image in each comparison. The image quality is measured in the terms of the PSNR and the maximum absolute error (MAE) that is

$$\mathrm{MAE} = \max_{x,y} \left| f(x,y) - \hat{f}(x,y) \right|. \tag{24}$$

From Table 3(a), conventional method 1 [8] embeds data to neither "Aerial 6" nor "Barbara," whereas the proposed method embeds 2622-bits and 31573-bits data into "Aerial 6" and "Barbara," respectively as shown in Table 2. Shifting pixel values in conventional method 1 was not applied in this experiment because doing so degrades the Image quality of stego images very much. Though modifying a coefficient in a transformed domain affects several pixels in the spatial domain, this conventional method avoid it by using modified 5×3 lifting wavelet transformation. This usage of the modified transformation, however, restricts the degrees of freedom in the embedding process. For the remaining six images, the proposed method is superior in terms of the PSNR of stego images to conventional method 1. In particular, the proposed method is about 16 dB superior than conventional method 1 for "Sailboat."

The RS method [9] is compared to the proposed method (Table 3(b)). This conventional method first fixes one parameter A for images that results in suppressing MAE to the fixed value. Here, A is set to five for "Aerial 6" and to seven for the other images. The payload only indicates the amount of data to be hidden; it excludes the amount of the original state that is also embedded into images for recovering the original image from a stego image in conventional method 2. This conventional method can hide data in all eight images as well as the proposed method. The proposed

Table 3 Comparisons with the conventional methods in terms of the image quality of stego images. The payload is maximally set to the actual capacity of the conventional methods.

(a) With the conventional method 1 [8] (This conventional method embeds data to neither Aerial 6 nor Barbara).

Image	Payload [bits]	PSNR [dB]		MAE	
		Conv. 1 [8]	Proposed	Conv. 1 [8]	Proposed
Aerial 6	0	—	—	—	—
Airplane	2356	57.6	63.2	49	5
Barbara	0	—	—	—	—
Baboon	4733	50.9	53.4	34	21
Lena	2615	57.9	60.8	14	17
Peppers	2787	50.1	59.5	27	16
Sailboat	87	64.1	80.4	23	3
Tiffany	456	59.1	72.1	29	5

(b) With the conventional method 2 [9] (Parameter A is set to five for "Aerial 6" and to seven for others).

Image	Payload [bits]	PSNR [dB]		MAE	
		Conv. 2 [9]	Proposed	Conv. 2 [9]i	Proposed
Aerial 6	2187	37.7	65.9	6	9
Airplane	17196	34.8	55.9	7	11
Barbara	3463	34.8	55.0	7	8
Baboon	7786	34.8	56.1	7	36
Lena	12995	34.8	51.0	7	19
Peppers	11414	34.8	50.8	7	16
Sailboat	7685	34.8	53.4	7	15
Tiffany	17048	34.8	52.9	7	11

(c) With the conventional method 3 [10] (Threshold T is employed).

Image	Payload [bits]	PSNR [dB]		MAE	
		Conv. 3 [10]	Proposed	Conv. 3 [10]	Proposed
Aerial 6	2622	51.5	65.0	11	9
Airplane	63474	43.6	40.1	11	59
Barbara	31573	41.2	47.3	11	23
Baboon	34548	44.2	38.8	11	79
Lena	60451	42.2	41.2	11	47
Peppers	60006	42.2	42.3	11	50
Sailboat	64444	40.6	36.3	11	65
Tiffany	59025	42.5	43.3	11	35

method is superior in terms of the PSNR of stego images to conventional method 2. In particular, for "Aerial 6," the proposed method improves by about 28 dB from conventional method 2.

The comparison between the proposed method and conventional method 3 [10] is summarized in Table 3(c). This conventional method must embed the original state in addition to data to be hidden, and the payload presented in Table 3(c) is only the amount of data to be hidden. For some images, conventional method 3 is superior to the proposed method in the terms of the PSNR. By employing threshold T, conventional method 3 increases the capacity. For fixed size payload, it increases the degree of freedom for choosing pixel pairs in which data are hidden, and this resulted in giving the better image quality and fixed MAE. However, conventional method 3 chooses T according to its embedding manner that requires calculation twice for one T; once using horizontal pixel pairs and then using vertical pixel pairs. Furthermore, it is noted that the rooms for performance improvement still exist in the proposed method by using another sized and shaped block, another placement of blocks, and embedding equation [11].

In addition to the comparisons in the terms of image quality, the compression performance were evaluated. The original and stego images are losslessly compressed done by an encoder [13] for JPEG 2000 [14] that is an ISO international standard. Stego images conveying the maximum payload that most degrade compression performance are used for evaluation, i.e., "Baboon" for conventional method 1, "Airplane" for conventional method 2, and "Sailboat" for conventional method 3. Compression ratios are summarized in Table 4. The proposed method slightly degrades the compression ratio (Tables 4(a) and (b)) and is similar to conventional methods 1 and 3 in terms of deterioration on the compression ratio (Tables 4(a) and (c)).

Table 4 Influence of data hiding on compression (original and stego images are losslessly compressed by a JPEG 2000 [14] encoder [13]).

(a) With the conventional method 1 [8] (4733 bits data embedded to "Baboon").

Original image	Proposed method	Conventional method 1 [8]
0.579	0.583	0.583

(b) With the conventional method 2 [9] (17196 bits data embedded to "Airplane").

Original image	Proposed method	Conventional method 2 [9]
0.273	0.286	0.454

(c) With the conventional method 3 [10] (64444 bits data embedded to "Sailboat").

Original image	Proposed method	Conventional method 3 [10]
0.439	0.495	0.482

5. Conclusions

A lossless embedding method that inserts data in an image in the spatial domain has been proposed. The proposed method embeds and extracts data by using only one parameter that is based on the statistics of surrounding pixels of stego pixels. Because this method can easily guarantee losslessness, it can utilize the degree of freedoms in the embedding process in comparison with the conventional methods. The proposed method, thus, improves the capacity for hidden data and the image quality of stego images, simultaneously. This method recovers the original image as well as extracts hidden data from a stego image. Moreover, the method requires neither any reference images nor knowledge of the location of pixels actually conveying hidden data to extract embedded data. In addition, this method can control the capacity and the quality of a stego image by controlling the parameter.

The proposed method has other degrees of freedom in the size, shape, and placement of pixel blocks, and in embedding equations [11]. Further works include the generalization of the method through consideration of these degrees of freedom.

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Hong Lin Jin received his B.Sci. degree from Yanbian University, the P.R.C. in 1987 and his M.Sci. degree from Hirosaki University, Japan in 2004. From 1987 to 2000, he was with Yanbian Agriculture College, the P.R.C. Since 2005, he has been a Ph.D. candidate at Tokyo Metropolitan University, Japan. His research interests include image processing and security for multimedia.

Masaaki Fujiyoshi received his B.Arts, M.Eng., and Ph.D. degrees from Saitama University, Japan in 1995, 1997, and 2001, respectively. In 2001, he joined Tokyo Metropolitan University, Japan, where he is currently a Research Associate of Information and Communication Systems Engineering, Faculty of System Design. His research interests include image processing, secure communications, and spread spectrum communications. Dr. Fujiyoshi served as an Associate Editor for the Special Section on Selected Papers from the 19th Workshop on Circuits and Systems in Karuizawa of the IEICE Trans. Fundamentals. He has also served as an Associate Editor for the J. IEICE from 2005. He has been a Member of the Smart Infomedia Systems Committee of the IEICE from 2005. He is also a Member of the ITE (Institute of Image Information and Television Engineers, Japan) and the IEEE. He received the Young Engineer Award from the IEICE in 2001.

Hitoshi Kiya received his B.E. and M.E. degrees from Nagaoka University of Technology, Japan in 1980 and 1982, respectively, and his D.E. degree from Tokyo Metropolitan University, Japan in 1987. In 1982, he joined Tokyo Metropolitan University, where he is currently a Professor of Information and Communication Systems Engineering, Faculty of System Design. He was a Visiting Fellow at the University of Sydney, Australia from Oct. 1995 to March 1996. His research interests include digital signal processing, multirate systems, adaptive filtering, image processing, and security for multimedia. Prof. Kiya served as an Associate Editor for the IEICE Trans. Fundamentals (Japanese Edition) and the IEEE Trans. Signal Processing from 1998 to 2002 and from 1998 to 2000, respectively. He served as the Guest Editor for the Special Sections on Papers Selected from ITC-CSCC 2005 and on VLSI for Digital Signal Processing of the IEICE Trans. Fundamentals. He has been a vice chair of the Signal Processing Committee of the IEICE and the chair of the Media Engineering Committee of the ITE (Institute of Image Information and Television Engineers, Japan) from 2005. He is a Member of the ITE and the IIEEJ (Institute of Image Electronics Engineers of Japan), and a Senior Member of the IEEE.