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Reversible DCT-based data hiding in stereo images

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Abstract Stereo images captured from a pair of CCDs simultaneously are widely used to create the illusion of 3D depth. Each pair of stereo images has many similar block pairs. In this paper, a novel reversible data hiding method is proposed to embed secret data in these similar block pairs. To increase the embedding capacity, each 3-bit secret data is first converted to a pair of integers. Then, similar block pairs are found based on the lower frequency DCT-quantized coefficients. Each converted integer is embedded via the difference of a pair of middle frequency DCT-quantized coefficients from these similar block pairs. It is worth mentioning that the proposed method is reversible, but the existing data hiding methods for stereo images are irreversible. Experimental results show that the proposed method is undetectable under Chi-square analysis, and it provides high embedding capacity while maintaining acceptable quality of stereo images higher than 30 dB. The experimental results also show that the proposed method outperforms Chang et al.'s method and Lin and Shiu's method in embedding capacity and image quality.

Keywords Stereo images · Data hiding · Quantized DCT coefficients

1 Introduction

Data hiding techniques have been widely studied in privacy community [4, 6]. Most methods distort cover median. However, for some applications, cover media should not be distorted, these include medical images, military images, or forensic images (provided by law) [5]. To solve this problem, recently, reversible data hiding techniques [3, 5, 7, 8, 11–13, 15, 17, 18] were proposed for perfectly recovering the original cover media.

In the spatial domain, Tian [15] proposed a reversible data hiding method, which expands the differences between pairs of pixels and then embeds one bit in each expanded difference. The main drawback is that after data embedding, some pairs of pixels may be overflow or underflow, and they cannot be used for secret message embedding. To treat this problem, a location map indicating whether a pair of pixels embeds any message or not is needed in the

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extraction process. The overhead for storing the map is 0.5 bit per pixel (bpp). Lee et al. [7] proposed a reversible steganographic method, which uses a 2×2 block as an embedding unit to reduce the capacity for storing the map to 0.25 bpp. Zhang [18] proposed a new reversible data hiding method which provides the optimal rule of host pixel value modification under a payload-distortion criterion. The optimal value transfer matrix is found by maximizing a target function of payload with an iterative procedure. Qin et al. [11] proposed a special reversible data hiding scheme for VQ-compressed images using index mapping mechanism. In the same year, they [12] proposed a new prediction-based reversible steganographic scheme based on image inpainting to obtain higher embedding capacity and lower distortion. In the frequency domain, Chang et al. [3] provided a reversible data hiding method for hiding secret data in quantized DCT coefficients of JPEG images. Lin and Shiu [8] improved Chang et al.'s method [3] and proposed a DCT-based reversible data hiding method with higher embedding capacity. Wong and Tanaka [17] provided a scrambling method in the DCT domain while inserting external information into the content. Rengarajaswamy and Vel Murugan [13] proposed a separable reversible data hiding method based on encrypted and transform in compressed images.

Recently, a technique called stereoscopy is widely used to create the illusion of 3D depth from a pair of given 2D images, called stereo images, which are captured from a pair of CCDs simultaneously. Chiang and Bai [1] proposed a data hiding method based on binocular fusion for stereo images. The embedding data are hidden in the depth field of a stereo pair through manipulating the pixel values of one of the stereo pair. Campisi [2] proposed an object-oriented digital watermark scheme for a pair of stereo images. The scheme first extracts a depth map from a pair of stereo images. Then, based on the depth map, each image is segmented into several regions. And the watermark will be embedded in each region through the high-frequency sub-bands of the wavelet decomposition. Shrikalaa et al. [14] proposed a stereo images data hiding method based on least significant bit (LSB) replacement. The stereo images are first embedded the secret message by replacing the LSB plane. Then, a pair of stereo images is converted to a single 3D stereo image using Random Sampling and Consensus (RANSAC) procedure. Luo et al. [9] proposed a stereo image watermarking for authentication with self-recovery capacity using inter-view reference sharing. The method can improve accuracy of tamper detection. The above mentioned methods are all irreversible. As the price of stereo equipment is reduced, stereo images exist around us gradually. For medical, military, or forensic applications, the data hiding method with reversible property is needed. In fact, to hide secret data in stereo images for medical, military, or forensic applications, existing reversible data hiding methods can be applied independently to each image. However, this approach does not utilize the characteristic of stereo images.

In this paper, a novel reversible data hiding method for stereo images is proposed. The method is based on the property that a pair of stereo images has many similar blocks. First, each 3 bit secret data is converted into a pair of integers in [−1, 1]. Second, for each block in the left image, the most similar block in the right image is found based on some DCT-quantized coefficients with lower frequencies. Each converted integer is then embedded via the difference of a pair of DCT-quantized coefficients with the same middle frequencies in two similar blocks. Note that for each integer embedding, only one of the pair of coefficients is changed, and the absolute changed value is at most 1. This makes the stego stereo images have good quality. Furthermore, since the human vision system is more sensitive to noise in the lower frequency, to maintain the image quality, only some middle frequency DCT-quantized coefficients are modified. The proposed method is reversible. Experimental results show that the proposed method provides high embedding capacity.

The rest of this paper is organized as follows. In Section 2, we present the proposed method. Steganalysis and experimental results are given in Section 3. Finally, conclusions are made in Section 4.

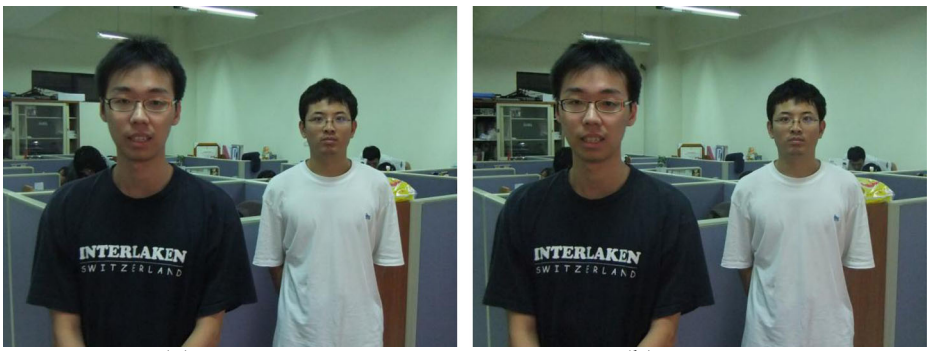
2 Proposed method

The proposed method is based on a fact that a pair of stereo images looks very similar. Figure 1 shows an example of a pair of stereo images produced by Fuji FinePix REAL 3D W1 camera. Figure 1a shows the image taken by the left CCD and Fig. 1b shows the image taken by the right CCD. These two images look similar and have many similar block pairs. This is an important property of stereo images.

Based on this property, we proposed a reversible method to embed secret data through similar block pairs in the DCT domain. The proposed method contains two procedures: embedding and extraction. In the embedding procedure, each image is first divided into 8 × 8 blocks in the DCT domain, each block is divided into three areas with different DCT frequencies as shown in Fig. 2. One contains some lower-frequency DCT-quantized coefficients called searching area, one contains some middle-frequency DCT-quantized coefficients called embedding area, and the other contains other non-used coefficients called non-used area. Next, similar block pairs between a pair of stereo images are found based on the searching area. Then, for each pair of similar blocks, a secret data is embedded in a certain middle-frequency DCT-quantized coefficient from one of the similar block pair. In order to keep security, for each secret data embedding, a stego key is used to randomly choose the embedding image. Note that the embedding area is different from the searching area, this makes sure that the result of similar block search in the extraction procedure is the same as that in the embedding procedure. The extraction procedure is similar to the embedding procedure. The details are described as follows.

2.1 Embedding procedure

In order to increase the embedding capacity, each 3-bit message $b_2b_1b_0$ is converted into two integers z_0 and z_1 in interval [−1, 1] before embedding. Then, for each 8×8 block in the left image, the most similar 8×8 block in the right image is first found. The similarity measure is based on the differences of the similar blocks in the searching area. Next, the differences



(a) Left image. (b) Right image.

Fig. 1 An example of a pair of stereo images. **a** Left image. **b** Right image

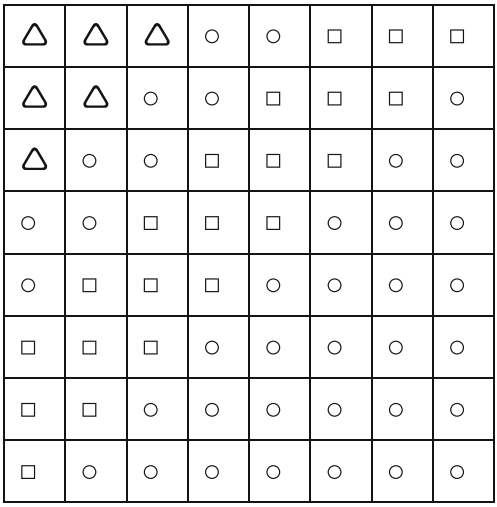


Fig. 2 Three areas of a 8 × 8 block in the DCT domain. (*White triangle*: searching area. *White square*: embedding area. *White circle*: non-used area)

between the embedding area of the similar block pair are computed. Then, those differences with zero values are used to embed secret data. Other differences with non-zero values are shifted 1. A stego key is used to choose the embedding image to meet the security issue. The details are described in the following Subsections.

2.1.1 Secret data conversion

Our embedding function is designed to embed an integer ∈ [−1, 1] in a pair of coefficients. Thus, each pair of coefficients can embed about 1.59 bits (more than 1 bit and less than 2 bits). If we combine two pairs of coefficients into a unit, each unit can represent 9 different combinations. That is, each unit can embed about 3.17 bits (more than 3 bits and less than 4 bits). Therefore, to get a high embedding capacity, we adopt two pairs of coefficients to embed 3-bit message. To reach this aim, 3-bit secret data are chosen to convert for a pair of integers. Each integer is embedded in one pair of coefficients.

Let $b_2b_1b_0$ be a 3-bit message, it can be converted into two integers z_0 and z_1 in interval [−1, 1] through following steps:

Step 1. Let $D=4b_2+ 2b_1+ b_0$.
Step 2. D is converted into a 3-based integer with two digits t_0 and t_1,

$$t_0 = D \mod 3, \tag{1}$$

$$t_1 = (D - t_0) \Big/ 3, \tag{2}$$

where *mod* stands for modulo operation.
Step 3. Obtain z_0 and z_1 from t_0 and t_1,

$$z_k = \begin{cases} t_k, & \text{if } t_k \le 1 \\ -1, & \text{if } t_k = 2 \end{cases}, \text{for } k = 0, \ 1. \tag{3}$$

2.1.2 Similar block searching

Each image is divided into $M \times N$ non-overlap blocks, each block has 8×8 pixels. For each block $B^L_{m,n}$ ($0 \le m \le M$ - 1, $0 \le n \le N$ - 1) in the left image, the most similar block $CorrB_{m,n}$ in the right image can be found through following steps:

Step 1. For each block $B^R_{m+i,n+j}$ in the right image with $-K \le i, j \le K$, calculate the difference of the searching area between the block and $B^L_{m,n}$ according to the following equation:

$$Dif\left(B^R_{m+i,n+j}\right) = \sum_{u,v=0}^{u+v<3} \left[C_{B^L_{m,n}}(u,v) - C_{B^R_{m+i,n+j}}(u,v)\right]^2, \tag{4}$$

where $C_B(u, v)$ stands for the DCT-quantized coefficient at (u, v) in block B.

Step 2. Let

$$CandB_{m,n} = \arg \min_{B^R_{m+i,n+j}} \left\{Dif\left(B^R_{m+i,n+j}\right), -K \le i, j \le K\right\}, \tag{5}$$

$$MinD_{B_{m,n}} = \min_{-K \le i,j \le K} \left\{Dif\left(B^R_{m+i,n+j}\right)\right\}. \tag{6}$$

Step 3. Given a threshold T, the most similar block $CorrB_{m,n}$ in the right image is found according to the following equation:

$$CorrB_{m,n} = \begin{cases} CandB_{m,n}, & \text{if } MinD_{B_{m,n}} \le T, \\ null \quad , & \text{otherwise} \quad . \end{cases} \tag{7}$$

Note that in our experiment, we set K=10, and find that the most similar blocks $CorrB_{m,n}$ always appear in [−5, 5]. To avoid slowing down the searching performance, we suggest to set K =5.

2.1.3 Data embedding

In the embedding process, the pixel values of an embedded block after applying the IDCT may result in overflow/underflow problems. That is, pixel values of an embedded block may exceed the maximal value (255 for 8-bit gray level image) or may be smaller than the minimal value (0 for 8-bit gray level image). Here, we provide a scheme to treat this problem. In this scheme, block pairs in stereo images are classified into two categories: non-embeddable block pairs (NEBPs) and embeddable block pairs (EBPs). For each block in the left image, the LSB of the DCT-quantized coefficient at u=2, v=2 is used to indicate if secret data are embedded or not in a block pair.

Before embedding data, differences of the embedding area between $B^L_{m,n}$ and $CorrB_{m,n}$ are calculated by the following equation:

$$dif_{B_{m,n}}(u,v) = C_{B^L_{m,n}}(u,v) - C_{CorrB_{m,n}}(u,v), 4 < u + v < 8. \tag{8}$$

Then, each (u, v) with $dif_{B_{m,n}}(u,v) = 0$ is used to embed a secret integer z according to the following steps:

Step 1. Let

$$dif'_{B_{m,n}}(u,v) = \begin{cases} dif_{B_{m,n}}(u,v) + 1, & \text{if } dif_{B_{m,n}}(u,v) > 0, \\ z \quad , & \text{if } dif_{B_{m,n}}(u,v) = 0, \\ dif_{B_{m,n}}(u,v) - 1, & \text{if } dif_{B_{m,n}}(u,v) < 0. \end{cases} \tag{9}$$

Step 2. A pseudo random number generator (*PRNG*) is used to generate a random bit, which is used to select one embedding coefficient from the left or right image. Note that we use a stego key K as the initial seed of *PRNG*. The selected coefficient is modified by the following equations:

$$C'_{B^L_{m,n}}(u,v) = \begin{cases} C_{B^L_{m,n}}(u,v) \quad , & \text{if } PRNG(z) = 1, \\ C_{CorrB_{m,n}}(u,v) + dif'_{B_{m,n}}(u,v), & \text{if } PRNG(z) = 0, \end{cases} \tag{10}$$

$$C'_{CorrB_{m,n}}(u,v) = \begin{cases} C_{B^L_{m,n}}(u,v) - dif'_{B_{m,n}}(u,v), & \text{if } PRNG(z) = 1, \\ C_{CorrB_{m,n}}(u,v) \quad , & \text{if } PRNG(z) = 0. \end{cases} \tag{11}$$

Note that $PRNG(z)$ denotes the random generated bit when embedding z in the quantized DCT coefficient (u, v), $4<u+v<8$. When it is 1, then the right image is used to embed z; otherwise, the left image.

Step 3. Check if the block pair is embeddable. The LSB of $C'_{B^L_{m,n}}(2,2)$ is added to the secret massage. Set the LSB of $C'_{B^L_{m,n}}(2,2)$ to be 1. Apply IDCT to each embedded block and check if any pixel value is overflow or underflow. If yes, go to Step 4.

Step 4. Restore all DCT coefficients in the block pair. Set the LSB of $C'_{B^L_{m,n}}(2,2)$ to be 0.

Note that in our experiments, we do not find any overflow/underflow problems. Thus, in the following, we do not treat the overflow/underflow problems.

2.1.4 Example of embedding

Here, an example is given in Fig. 3 to do more explanation for the proposed embedding procedure. Figure 3a shows the DCT-quantized coefficients of a block in Figs. 1a and 3b shows the most similar block of Fig. 3a in Fig. 1b. Before embedding data, differences of the embedding area between these two blocks are calculated through Eq. 8, and the result is shown in Fig. 3c. Note that only zero difference can be used to embed data, there are 16 zero differences in Fig. 3c. Thus, 24 bits secret message (**110110000011100001000010**) can be embedded, and they are converted to 16 secret integers (0, −1, 0, −1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 0, −1, 0) through the proposed data conversion. These 16 secret integers are then embedded through Eq. 9 from left to right and top to bottom, and the result is shown in Fig. 3d. Finally, a pseudo random number generator generates a sequence (1, 0, 0, 0, 1, 1, 0, 1, 0, 1, 0, 1, 1, 1, 0, 1, 0, 0, 1, 1, 0), which is employed to select a block for data embedding according to Eqs. 10–11, the results are shown in Figs. 3e and f. Note that the bold squares in Figs. 3e and f indicate the modified coefficients.

88	1	0	3	0	**0**	**0**	**0**
1	0	1	2	**1**	**0**	**0**	0
4	2	-2	**0**	**1**	**0**	0	0
-1	2	**0**	**0**	**0**	0	0	0
-1	**-1**	**0**	**0**	0	0	0	0
-1	**0**	**0**	0	0	0	0	0
0	**0**	0	0	0	0	0	0
0	0	0	0	0	0	0	0

(a) The original quantized DCT coefficients of block (322,368) in Fig. 1(a).

88	0	0	-1	1	**0**	**0**	**0**
0	1	-3	-1	**-1**	**0**	**0**	0
4	0	3	**1**	**0**	**0**	0	0
3	-4	**0**	**1**	**0**	0	0	0
1	**0**	**0**	**0**	0	0	0	0
-1	**0**	**0**	0	0	0	0	0
0	**0**	0	0	0	0	0	0
0	0	0	0	0	0	0	0

(b) The original quantized DCT coefficients of block (323,363) in Fig. 1(b).

					0	**0**	**0**
				2	**0**	**0**	
			-1	**1**	**0**		
		0	**-1**	**0**			
	-1	**0**	**0**				
0	**0**	**0**					
0	**0**						
0							

(c) The differences (*dif*) between (a) and (b) at (u, v) with $4 < u + v < 8$.

					0	**-1**	**0**
				3	**-1**	**0**	
			-2	**2**	**0**		
		0	**-2**	**1**			
	-2	**1**	**1**				
1	**0**	**0**					
0	**-1**						
0							

(d) The differences (*dif'*) after data embedding.

88	1	0	3	0	**0**	**-1**	**0**
1	0	1	2	**2**	**0**	**0**	0
4	2	-2	**-1**	**1**	**0**	0	0
-1	2	**0**	**-1**	**0**	0	0	0
-1	**-1**	**0**	**1**	0	0	0	0
-1	**0**	**0**	0	0	0	0	0
0	**0**	0	0	0	0	0	0
0	0	0	0	0	0	0	0

(e) The final result of (a).

88	0	0	-1	1	**0**	**0**	**0**
0	1	-3	-1	**-1**	**1**	**0**	0
4	0	3	**1**	**-1**	**0**	0	0
3	-4	**0**	**1**	**-1**	0	0	0
1	**1**	**-1**	**0**	0	0	0	0
-2	**0**	**0**	0	0	0	0	0
0	**1**	0	0	0	0	0	0
0	0	0	0	0	0	0	0

(f) The final result of (b).

Fig. 3 An example of embedding 16 integers in a pair of blocks. **a** The original quantized DCT coefficients of block (322,368) in Fig. 1(a). **b** The original quantized DCT coefficients of block (323,363) in Fig. 1(b). **c** The differences (*dif*) between (a) and (b) at (u, v) with $4<u+v<8$. **d** The differences (*dif '*) after data embedding. **e** The final result of (a). **f** The final result of (b)

2.2 Extraction procedure

The extraction procedure is similar to the embedding procedure. First, each image is divided into $M \times N$ non-overlap blocks. For each block in the left image, we find out the most similar block in the right image. Note that the embedding area are different from the searching area. Therefore, the similar blocks found before and after data embedding are the same. Then, the secret data can be extracted from similar block pairs. The details are given as follows:

Step 1. Generate a random sequence based on the stego key.

Step 2. Divide each of the stego stereo images into $M \times N$ blocks.

Step 3. For each block $B^L_{m,n}$ ($0 \le m \le M$-1, $0 \le n \le N$-1) with DCT-quantized coefficients in the left image, find out the most similar block $CorrB_{m,n}$ in the right image through Eqs. 4–7.

Step 4. Calculate differences of the embedding area between $B^L_{m,n}$ and $CorrB_{m,n}$ according to Eq. 8.

Step 5. Extract the secret integer z according to the following equation:

$$z = dif_{B_{m,n}}(u,v), \text{if} -1 \le dif_{B_{m,n}}(u,v) \le 1. \tag{12}$$

Step 6. Restore the original difference according to the following equation:

$$dif'_{B_{m,n}}(u,v) = \begin{cases} dif_{B_{m,n}}(u,v) - 1, & \text{if } dif_{B_{m,n}}(u,v) > 1, \\ 0 \quad , & \text{if} -1 \le dif_{B_{m,n}}(u,v) \le 1, \\ dif_{B_{m,n}}(u,v) + 1, & \text{if } dif_{B_{m,n}}(u,v) < -1. \end{cases} \tag{13}$$

Step 7. Restore the original coefficients through Eqs. 10 and 11 and $PRNG(z)$.

Step 8. Repeat Steps 3–7 until all blocks in the left image are processed.

Step 9. Restore the secret message for each pair of extracted secret integers z_0 and z_1 through the following equations:

$$t_k = \begin{cases} z_k, & \text{if } z_k \geq 0\,, \\ 2, & \text{if } z_k = -1, \end{cases} \tag{14}$$

$$D = t_0 + 3t_1. \tag{15}$$

Step 10. Convert D into a 2-based 3 digit number.

An example is given in Fig. 4 to do more explanation for the extraction procedure. Figure 4a shows the differences between Figs. 3e and f according to Eq. 8. The secret integers are extracted from Fig. 4a according to Eq. 12, and results are shown in Fig. 4b. The extracted integers are the same as the embedded secret integers (0, −1, 0, −1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 0, −1, 0) mentioned in Section 2.1.4. Then, the extracted integers are converted to the secret message (**110110000011100001000010**) according to Step 9 and Step 10 in the extraction procedure. The extracted secret message is the same as the embedded secret message mentioned in Section 2.1.4. Figure 4c shows the restored differences, which are recovered according to Eq. 13 and are the same as those in Fig. 3c. Figures 4d and e show the restored DCT-quantized coefficients through Eqs. 10 and 11. Note that Figs. 4d and e are exactly the same as Figs. 3a and b.

3 Experimental results

In our experiments, we used two stereo image datasets, one contains 21 pairs of stereo images from Middlebury stereo datasets [10], and the other has 7 pairs of stereo images produced by

					0	**-1**	**0**
				3	**-1**	**0**	
			-2	**2**	**0**		
		0	**-2**	**1**			
	-2	**1**	**1**				
1	**0**	**0**					
0	**-1**						
0							

(a) The differences between Fig.3(e) and Fig.3(f).

					0	**-1**	**0**
					-1	**0**	
					0		
			0		**1**		
		1	**1**				
	1	**0**	**0**				
	0	**-1**					
	0						

(b) The extracted secret data.

					0	**0**	**0**
				2	**0**	**0**	
			-1	**1**	**0**		
		0	**-1**	**0**			
	-1	**0**	**0**				
0	**0**	**0**					
0	**0**						
0							

(c) The restored differences

88	1	0	3	0	**0**	**0**	**0**
1	0	1	2	**1**	**0**	**0**	0
4	2	-2	**0**	**1**	**0**	0	0
-1	2	**0**	**0**	**0**	0	0	0
-1	**-1**	**0**	**0**	0	0	0	0
-1	**0**	**0**	0	0	0	0	0
0	**0**	0	0	0	0	0	0
0	0	0	0	0	0	0	0

(d) The restored coefficients of Fig. 3(e)

88	0	0	-1	1	**0**	**0**	**0**
0	1	-3	-1	**-1**	**0**	**0**	0
4	0	3	**1**	**0**	**0**	0	0
3	-4	**0**	**1**	**0**	0	0	0
1	**0**	**0**	**0**	0	0	0	0
-1	**0**	**0**	0	0	0	0	0
0	**0**	0	0	0	0	0	0
0	0	0	0	0	0	0	0

(e) The restored coefficients of Fig.3(f)

Fig. 4 An example of extracting secret data and restoring DCT-quantized coefficients in a corresponding stego block pair. **a** The differences between Fig. 3e and f. **b** The extracted secret data. **c** The restored differences. **d** The restored coefficients of Fig. 3e. **e** The restored coefficients of Fig. 3f

Fuji FinePix REAL 3D W1 camera. Figures 5 and 6 show four pairs of stereo images from these two datasets, respectively.

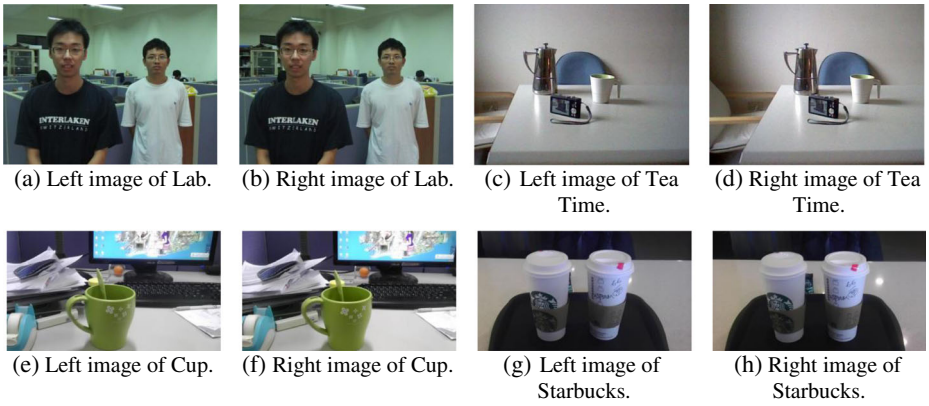
Chang et al.'s method [3] and Lin and Shiu's method [8] are designed for general JPEG images. We apply their method to each of stereo images to do comparison. The proposed method uses threshold T (see Eq. 7) to decide if a pair of similar block pairs is used for data embedding. In the experiment, various thresholds are used to observe the impact on the image quality and embedding capacity. The secret data is a pseudo randomly generated bit sequence. The peak signal to noise ratio (PSNR) and bits per pixel (bpp) are used to evaluate the image quality and embedding capacity, respectively.

Table 1 shows the experimental results with average PSNR and embedding capacity of stego stereo image pairs from two stereo image datasets. From this table, we can see that a bigger threshold T allows more bits embedded, but makes PSNR lower. It also shows that our method can maintain the stego image quality higher than 35 dB and 31 dB in two stereo image datasets, respectively. According to the experimental results, setting the threshold T to 20 is enough for general usage. Furthermore, under the similar embedding capacity, the stego image quality of our proposed method is better than those of Chang et al.'s method [3] and Lin and Shiu's method [8] about 4.8 dB and 6.6 dB in Middlebury stereo datasets [10] and about 8 dB and 9.8 dB in stereo images produced by Fuji FinePix REAL 3D W1 camera, respectively, in terms of PSNR. Under the similar PSNR values, our proposed method can provide more embedding capacity than Chang et al.'s method [3] and Lin and Shiu's method [8] about 0.2 bpp and 0.45 bpp in Middlebury stereo datasets [10], respectively. Note that the proposed method maintains the stego image quality higher than 30 dB, Chang et al.'s method [3] can only obtain PSNR about 28 dB and Lin and Shiu's method [8] only obtain PSNR about 24 dB in stereo images produced by Fuji FinePix REAL 3D W1 camera. In addition, we also give the standard deviation values to show that the proposed method is stable.

(a) Left image of Aloe. (b) Right image of Aloe. (c) Left image of Baby1. (d) Right image of Baby1.

(e) Left image of Bowling1. (f) Right image of Bowling1. (g) Left image of Flowerpots. (h) Right image of Flowerpots.

Fig. 5 Four pairs of stereo images from Middlebury stereo datasets [10]. **a** Left image of Aloe. **b** Right image of Aloe. **c** Left image of Baby1. **d** Right image of Baby1. **e** Left image of Bowling1. **f** Right image of Bowling1. **g** Left image of Flowerpots. **h** Right image of Flowerpots



(a) Left image of Lab. (b) Right image of Lab. (c) Left image of Tea Time. (d) Right image of Tea Time.

(e) Left image of Cup. (f) Right image of Cup. (g) Left image of Starbucks. (h) Right image of Starbucks.

Fig. 6 Four pairs of stereo images produced by Fuji FinePix REAL 3D W1 camera. **a** Left image of Lab. **b** Right image of Lab. **c** Left image of Tea Time. **d** Right image of Tea Time. **e** Left image of Cup. **f** Right image of Cup. **g** Left image of Starbucks. **h** Right image of Starbucks

To further prove that the proposed method can withstand a Chi-square attack. We implemented a Chi-square test by [16] to perform Chi-square analysis. The Chi-square analysis is described as follows:

1. For an image, all gray values are divided into k categories. The ith category contains all pixels with gray values $2i$ and $2i+1$.
2. The theoretically expected frequency of gray value $2i$ after embedding an equally distributed binary message is

$$n_i^* = \frac{|\{\text{gray value} \in \{2i, 2i+1\}\}|}{2}. \tag{16}$$

Table 1 Experimental results of the image quality and embedding capacity with standard deviations

Method	T	Quality (PSNR)		Capacity (bpp)	
		Middlebury stereo datasets [10] μ (σ)	by Fuji FinePix REAL 3D W1 camera μ (σ)	Middlebury stereo datasets [10] μ (σ)	by Fuji FinePix REAL 3D W1 camera μ (σ)
Proposed method	5	43.24(3.43)	37.84(3.10)	0.12(0.08)	0.14(0.11)
	10	40.98(3.35)	34.63(1.36)	0.21(0.12)	0.24(0.11)
	15	39.52(2.75)	33.20(0.68)	0.26(0.12)	0.31(0.09)
	20	38.54(2.22)	32.56(0.65)	0.30(0.11)	0.34(0.08)
	25	37.86(1.86)	32.18(0.72)	0.34(0.10)	0.37(0.08)
	30	37.40(1.65)	31.91(0.80)	0.36(0.09)	0.38(0.07)
Chang et al.'s method [3]	N/A	37.17(2.17)	28.13(2.93)	0.17(0.07)	0.18(0.06)
Lin and Shiu's method [8]	N/A	32.72(1.94)	24.36(2.32)	0.24(0.09)	0.26(0.08)

μ denotes the mean value, σ denotes the standard deviation and N/A denotes non-available

3. The measured frequency of gray value $2i$ in the image is

$$n_i = \left|\{\text{gray value} = 2i\}\right|. \tag{17}$$

4. The χ^2 statistic is given as $\chi^2_{k-1} = \sum_{i=1}^{k} \frac{\left(n_i - n_i^*\right)^2}{n_i^*}$ with k-1 degrees of freedom.
5. Westfeld and Pfitzmann [13] provided the probability (p) of the statistic under condition that the distributions of n_i and n_i^* are equal. p is calculated as

$$p = 1 - \frac{1}{2^{\frac{k-1}{2}}\Gamma\left(\frac{k-1}{2}\right)} \int_0^{\chi^2_{k-1}} e^{-\frac{x}{2}} x^{\frac{k-1}{2}} dx. \tag{18}$$

When p is larger, it stands for more possibility of data embedding. Thus, we can consider p as the probability of embedding.

Because the proposed methods embed secret message in frequency domain, we apply Chi-square analysis to DCT-quantized coefficients of stego images. Figure 7 shows the results. X-axis stands for the sample rate from the test image. We can see that when 1-bit LSB replacement method is used, p is 1 in all sample rates. This means that the stego image embedded by 1-bit LSB replacement method can be detected by Chi-square analysis. ps for the original left image of Lab. and the stego images embedded by the proposed method are all 0 in sample rate more than 5 %. This means that the proposed method can pass the Chi-square analysis.

4 Conclusion

As the price of stereo equipment is reduced, stereo images exist around us gradually. To embed secret message on stereo images for medical, military, or forensic applications, we have

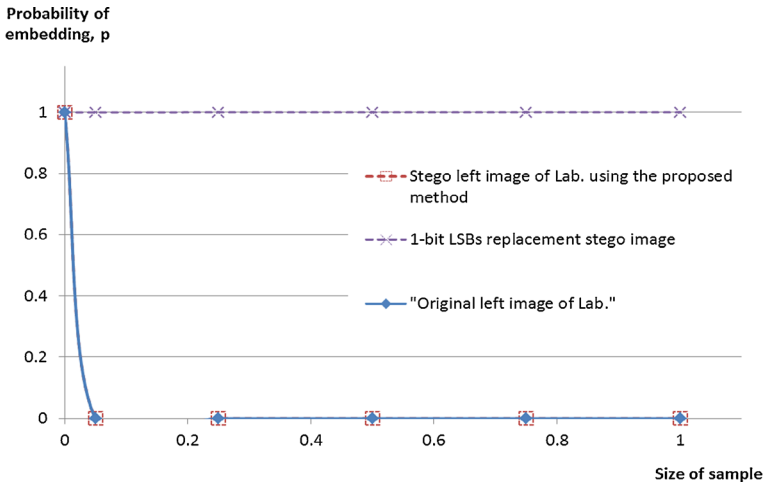


Fig. 7 Example of the left image of "Lab." for Chi-square analysis

proposed a novel DCT-based reversible data hiding method while maintaining acceptable quality of stereo images higher than 30 dBs.

The proposed method offers reversibility and high embedding capacity. In order to prevent overflow/underflow problems, we use one bit for each block pair to indicate if the block pair is embeddable or not. Thus, one bit overhead for each block pair is needed, compare to Tian's method and Lee et al.'s method, the overhead is minor. In fact, no overflow/underflow problems occur in the experiments. Thus, we did not use the overhead bit in all testing images. A transform that converts a 3-bit binary data into a pair of integers is proposed to increase the embedding capacity. Further, our method is undetectable under Chi-square analysis. Experimental results confirm that our proposed method outperforms Chang et al.'s method and Lin and Shiu's method in embedding capacity and image quality.

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