Stereo Image Coding with Histogram-Pair Based Reversible Data Hiding

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Abstract. This paper presents a stereo image coding method using reversible data hiding technique so that the right frame can be recovered losslessly and the left frame can be reconstructed with high visual quality. Utilizing the similarity between two frames in a stereo image pair the required size of storage and transmission bandwidth for the stereo image pair can be reduced to 50 %. A residual error matrix with a dynamic range of [−255, 255] is obtained by applying a frame-wise disparity algorithm which first shifts the left frame horizontally by a certain amount and then computes its difference to the right frame. Next, thus the generated residual error image with gray levels [0, 255] is obtained losslessly by a proposed labeling scheme. JPEG2000 lossy compression is then applied to the residual error image. The histogram-pair based reversible data hiding scheme is then utilized to embed the JPEG2000 lossy compressed data into the right frame. Compared with the prior art, which uses a block-based disparity estimation algorithm and a location map based reversible data hiding, the proposed method has demonstrated that the stereo image can be reconstructed with higher visual quality and with faster processing speed. Specifically, the experiments have demonstrated that both the PSNR and visual quality of the reconstructed stereo image pair are higher than those achieved by the prior arts.

Keywords: Stereo image coding · Histogram-pair based image reversible data hiding · Frame-wise algorithm · Labeling scheme

1 Introduction

With the rapid development of information technology, especially unprecedented computing capacity, stereo vision technology has made considerable progress and been applied widely in the fields like 3d TV etc. More and more vivid visual experiences are brought to people. But one stereo image pair is composed of two 2-D similar images,

its storage space and transmission bandwidth required may be twice larger than the traditional image applications. So it is important to develop efficient stereo image coding techniques to decrease the cost of the storing and transmitting stereo images.

Coltuc and Caciula proposed a method in [4] to solve this problem. Using the relation between two frames of a stereo image pair, they first achieved a residual error image by predicting the left frame using the right frame. Then the residual error image was applied lossy compression, and then reversibly embedded into the right frame. So only the marked right frame needed to be saved or transmitted as it contained the information of the whole stereo image. In the decoding end, the compressed residual error image can be losslessly retrieved from the right frame. With the retrieved error image and the right frame, the left frame can be reconstructed approximately. If the residual error image was embedded without going through the lossy compression, the left frame can be recovered losslessly as well. However, the capacity of reversible data hiding is usually unable to satisfy the requirement of saving all the information of the residual error image. Hence, the distortion to the left frame is unavoidable in [4].

In order to reduce the distortion, Coltuc [6] further proposed a dense disparity compensation scheme to decrease the information of the residual error image. This scheme calculates the disparity of every left frame point with SAD (sum of absolute differences). In consequence, better relevant information can be achieved and the quality of reconstructed left frame was enhanced. However, this way needs to record too much disparity information and hence leads to high computational complexity.

After that, Ellinas [5] and Chen [3] proposed the block-based disparity estimation and compensation schemes by. They divided the image into non-overlapping but connected blocks, and obtained the relevant information by searching the right frame for the matched block in the left frame. The SAD is used to evaluate the matching precision. The calculated relevant information is comprised of a disparity vector field and a residual error matrix. Although this method reduces the record information and computational complexity, the improvement is not obviously.

If every pixel of a frame is presented by an 8 bits number, the value range of the residual error matrix is [−255, 255]. And for the convenience of data compression, the residual error matrix should be preprocessed to generate a residual error image with value range constrained in [0, 255]. For instance, in [4–6], every pixel of the residual error matrix is first added by 255 and then divided by 2, followed by a ceiling operation to obtain the integer pixel value of the residual error image. In recovery, each pixel in the residual error image is multiplied by 2 and then minus by 255. It can be seen that the scheme adopted by [4] will generate distortion. To eliminate the distortion, a conditionally reversible preprocessing algorithm was proposed in [3]. Although the proposed scheme can eliminate distortion in some images, but in other images, the distortion always exits.In this paper we first propose a frame-wise disparity estimation algorithm to calculate residual error matrix. Then the residual error matrix is processed to a residual error image with value range [0, 255]. This process is lossless by means of a labeling scheme. Moreover, a more efficient reversible data hiding method named Histogram-Pair Based Reversible Data Hiding is proposed to increase the embedding capacity and improve the PSNR of the watermarked right frame. The experimental results show that both the PSNR and visual quality of the reconstructed stereo image pair are higher than that achieved by the prior arts [3–6].

2   Block Diagram of Proposed Stereo Image Coding

The stereo image transmission framework proposed in this paper is illustrated in Fig. 1. In the coding process, a stereo image pair is coded as a watermarked 2D image. Specifically it is the right frame with watermark hidden inside which can help us to reconstruct the left-frame approximately. In the receiver, the stereo image pair can be reconstructed if the stereo image decoder is conducted. Concretely, the right frame can be reconstructed exactly, while the left frame can be reconstructed closely to the original left frame. Without the above-mentioned processing at the receiver side, however, only a slightly degraded 2D right frame can be shown. Notations used in this paper are listed below.

L: the left frame of a stereo image pair
R: the right frame of the stereo image pair
$M \times N$: the size of the left and right frame
SAD: sum of absolute differences
P: the frame-wise disparity estimated according to SAD (the detailed definition will be given in Sect. 3)
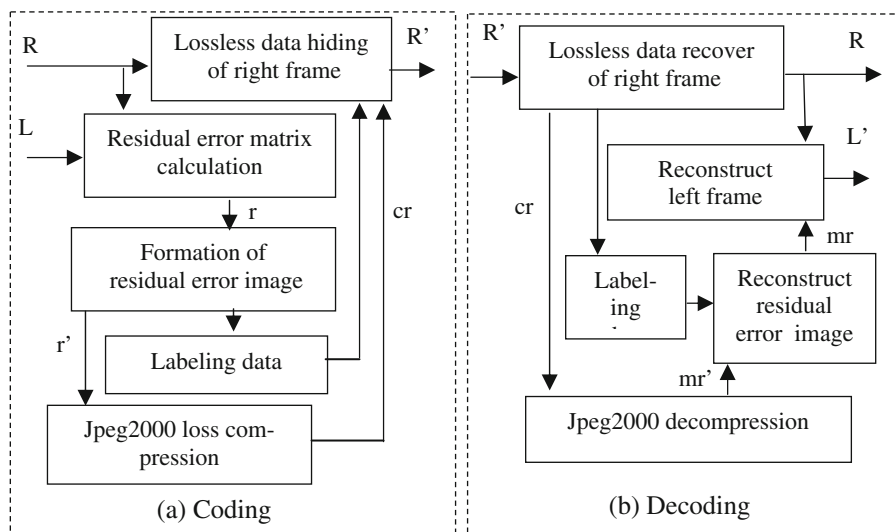r: residual error matrix of stereo image
r': residual error image obtained from r
cr: compressed residual error image
mr: recovered residual error image at end of decompression
mr': recovered residual error matrix obtained from mr
L': the left matrix reconstructed by mr and R

Fig. 1. Flowchart of proposed stereo image coding

3   Residual Information and Sum of Absolute Differences

This paper proposes a frame-wise disparity estimation algorithm, which also employs SAD (sum of absolute differences) to evaluate the similarity between frames. However, unlike the traditional estimation algorithms [3, 5, 6], we compute the SAD between two overall frames instead of a large number of blocks or pixels. Meanwhile, only one shifting offset, the left frame with respect to the right frame, need to be recorded. Apparently, the computational complexity of the estimation of disparity is greatly decreased. And we also note that the effect of the estimation is not obviously degraded because the stereo image pair are rather similar to each other. The detailed description is shown as follows.

Given a stereo image pair with size M × N, the frame-wise disparity can be calculated by:

$$P = \arg \min_{d}(SAD(d)), \quad m \leq d \leq n \tag{1}$$

Where d is the shifting offset of the left frame with respect to the right frame with a predefined value range in [m, n]. Although the offset could be with fraction implemented by image interpolation, we find integer is accurate enough for our disparity estimation. The difference between two frames SAD is calculated as follows,

$$
\begin{aligned}
SAD(d) = &\sum_{i=1}^{M} \sum_{j=1}^{d} |L(i,j) - R(i,1)| \\
&+ \sum_{i=1}^{M} \sum_{j=1}^{N-d} |L(i,j+d) - R(i,j)|, \quad m \leq d \leq n
\end{aligned}
\tag{2}
$$

Equation (2) consists of two terms. The first one is associated with the part of left frame that is shifted beyond the range of right frame. To obtain the difference between the two frames in this case, we just subtract the first column of the right frame from each column of this part of the left frame. The second term of Eq. (2) is associated with the rest part of the left frame. We compute the difference for the pixels in this part to the ones that are located at the same positions of the right frame. Furthermore, only horizontally shifting needs to be considered in the applications like 3D TV, as the 3D cameras are usually fixed with the same height. So we only add d to the horizontal coordinate of L. For example, if we set m = 1 and n = 9, the minimum SAD will be searched by shifting left frame from 1 to 9 pixels. Assuming it is $d = 6$ we obtain the minimum SAD, the frame-wise disparity P is equal 6.

Figure 2 illustrates our pipeline of calculating residual error matrix as well as disparity estimation. After the frame-wise disparity P has been calculated, the residual error matrix can be calculated by Eq. (3):

$$
r(i,j) = \begin{cases} L(i,j+P) - R(i,j) &, \quad 1 \leq i \leq M, \ 1 \leq j \leq N - P \\ L(i,j) - R(i,1) &, \quad 1 \leq i \leq M, \ 1 \leq j \leq P \end{cases}
\tag{3}
$$

We note again that in left frame the columns which are shifted beyond the right frame (i.e., the column number is smaller than P) should be corresponding to the first
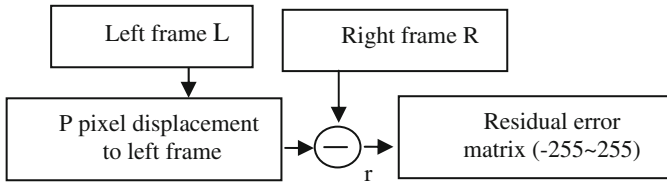
Fig. 2. Residual error matrix calculation

column of the right frame. Similarly, the procedure of reconstruction of the left frame
L' in the decoder end is also performed with two different manners, namely:

$$L'(i,j) = \begin{cases} mr(i,j+P) + R(i,j) & , \quad 1 \leq i \leq M, \ 1 \leq j \leq N-P \\ mr(i,j) + R(i,1) & , \quad 1 \leq i \leq M, \ 1 \leq j \leq P \end{cases} \tag{4}$$

Where *mr(.)* is the residual error matrix recovered at decoding end. Because of
JPEG2000 lossy compression performed in the encoding end (introduced in the next
section), *mr(.)* is not completely equal to r. So if there are pixels in L' beyond the
normal value range [0, 255], we just truncate them to 0 or 255.

4   Residual Error Image and Labeling Scheme

For a stereo image presented on 8 bits, the values in the residual error matrix r obtained
by Eq. (3) lie in [− 255, 255]. For the convenience of data compression, r should be
preprocessed to generate a grayscale residual error image denoted by r′ whose pixel
values are constrained to [0, 255].The scheme adopted by [4–6] are all irreversible and
adopted in [3] also generate distortion in some images. To eliminate distortion, labeling
scheme was proposed in this paper. According to our experimental results on many
stereo images downloaded from http://vision.middlebury.edu/stereo, we find most
points of a residual error matrix are in the range of [-127,127]. So we generate residual
error image by shrinking the histogram of the residual error matrix as illustrated in
Eq. (5) and Fig. 3.

In Eq. (5) the first line is associated with the points of residual matrix r ranging
from −128 to127 (B and C in Fig. 3). The second and third lines are corresponding to
region A and D in Fig. 3, respectively.

$$r'(i,j) = \begin{cases} 128 + r(i,j) & , \quad if \ -128 \leq r(i,j) \leq +127 \\ -r(i,j) - 129 & , \quad if \ r(i,j) < -128 \\ 128 + abs\{(r(i,j) - 255)\} & , \quad if \ r(i,j) > +127 \end{cases} \tag{5}$$

In order for reversibility, we need to record the positions of the points in A and D
regions of Fig. 3. Namely, if r (i, j) is greater than 127 or smaller than −128, we record
its coordinate (i, j), namely labeling in this paper. Because the frames of a stereo image
pair are rather similar to each other, only a limited amount of information needs to be
recorded. We will also embed this recorded information into right frame after
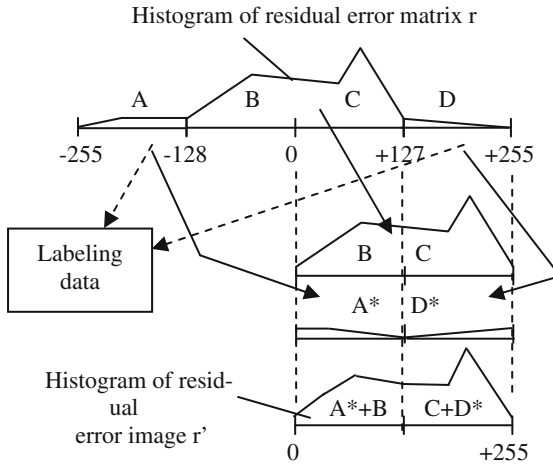
Fig. 3. Formation of residual error image by residual error matrix

compressed labeling data losslessly by using the adaptive arithmetic coding (AAC) algorithm [7].

Using the labeling scheme given in Eq. (5) and Fig. 3, we are able to losslessly transfer the residual error matrix to the residual error image, making it convenient to compress the residual via mature image coding method like JPEG2000. Our proposed labeling scheme consists of two functions, namely position recording and histogram shrinking. We note that in Fig. 3 and Eq. (5) the points in region A and D of the histogram are not simply shifted as shown in Fig. 4 and Eq. (6). Instead, we first invert A and D left to right before shifting them to merge with B and C.
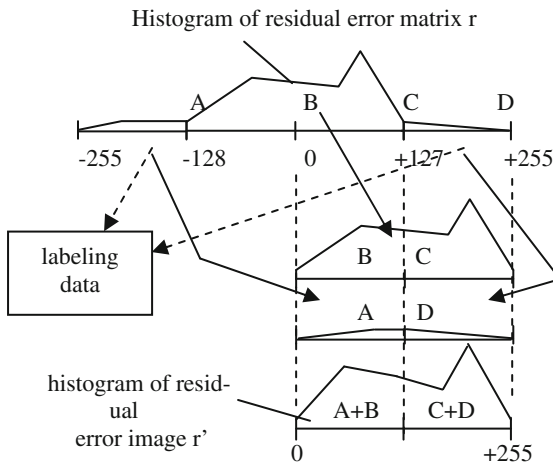
Fig. 4. Simple formation of residual error image by residual error matrix

The motivation reduces the change in pixel and maintains the spatial correlation between pixels in the residual error image. And experimental results show that using the shrinking method of Eq. (5) can improve the PSNR about 0.5 dB comparing that given by Eq. (6).

$$r'(i,j)_{Simple} = \begin{cases} 128 + r(i,j) & , & if \ -128 \leq r(i,j) \leq +127 \\ r(i,j) + 255 & , & if \ r(i,j) < -128 \\ r(i,j) & , & if \ r(i,j) > +127 \end{cases} \quad (6)$$

Because the lossy JPEG2000 compression and decompression, the recover residual error matrix mr' will have some digression from r'. Equation (7) shows how to recover the residual error matrix from the residual error image in the decoding end. The first line is at [0 ∼ − +255] or B and C in lower of Fig. 3. The second line is at [0 ∼ + 127] (before JPEG2000, the pixel gray level with labeling is only at the range [0 ∼ + 126]) or A* (reverse rank) in lower of Fig. 3. The third line is at [+ 128 ∼ − +255] or D* (reverse rank) in lower of Fig. 3.

$$mr(i,j) = \begin{cases} -128 + mr'(i,j) & , & if \ no \ labeling \ and \ 0 \leq mr'(i,j) \leq +255 \\ -255 + abs\{(mr'(i,j) - 126)\} & , & if \ with \ labeling \ and \ mr'(i,j) < +128 \\ 128 + abs\{(mr'(i,j) - 255)\} & , & if \ with \ labeling \ and \ mr'(i,j) \geq +128 \end{cases}$$
$$(7)$$

From Eqs. (5) and (7) and Fig. 3, we can see that the residual error image can be recovered with small distortion by lossy JPEG2000 compression and decompression only.

5 Large Payload Optimal Histogram-Pair Image Reversible Data Hiding

The data hiding approach employed in this paper is an extension of the one given in [2], namely our proposed Optimal Histogram-pair and Prediction-error based Image Reversible data hiding approach. The major improvement made here is that using multiple circles embedding scheme in order for large capacity of data hiding. The output image of each pass of circle embedding is the input image of the next pass (refer to Fig. 5 and Tables 1 and 2). The embedding capacity of the approach in [2] is 0.7bpp, which is satisfying for authentication. But it is not large enough for stereo image coding, because we cannot accomplish the coding unless the compression ratio on the left frame is smaller than 0.1 (0.7/8). In order to guarantee the high quality of recovery a data hiding approach with large capacity is required. With our newly proposed multiple circle embedding the embedding capacity is clearly improved, say, to 2.6bpp (5 pass) and 1.6 bpp (4 pass) for Baby and Tsukuba, respectively. The detailed setting of the data hiding approach used in this paper is given in Tables 1 and 2. In our implementation we employ the numbers of circle 4 and 6 for the two stereo images.

In order to explain the parameters involved in Tables 1 and 2, we simply introduce the process of our proposed histogram-pair based reversible data hiding approach.
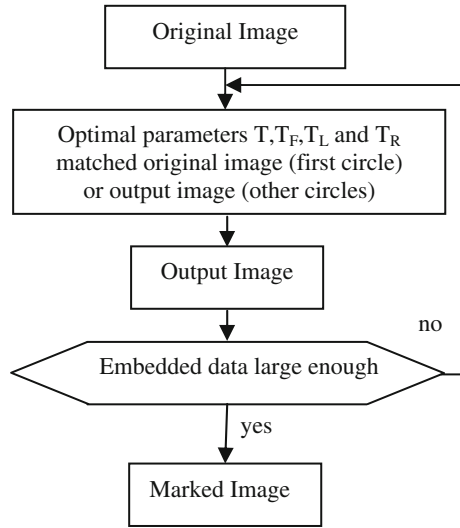
Fig. 5. Large payload by histogram-pair reversible data hiding using multi-circles

Table 1. Image Tsukuba embedding by histogram-pair based reversible data hiding

Circle	Payload (bpp)	PSNR (dB)	T	T_F	T_L	T_R	Image (original)	Δ Payload (bpp)	Image (marked)
1	0.8	37.71	4	350	7	5	Tsukuba	0.8	Tsukuba1
2	1.2	30.39	6	2500	6	6	Tsukuba1	0.4	Tsukuba2
3	1.5	24.48	14	6000	14	14	Tsukuba2	0.3	Tsukuba3
4	1.6	20.01	8	14000	8	9	Tsukuba3	0.1	Tsukuba4

Table 2. Image Baby embedding by histogram-pair based reversible data hiding

Circle	Payload (bpp)	PSNR (dB)	T	T_F	T_L	T_R	Image (original)	Δ Payload (bpp)	Image (marked)
1	1.0	41.51	−3	100	0	0	Baby	1.0	Baby1
2	1.6	33.98	6	800	0	0	Baby1	0.6	Baby2
3	2.0	28.88	12	3000	6	8	Baby2	0.4	Baby3
4	2.3	26.38	−4	5000	0	4	Baby3	0.3	Baby4
5	2.5	24.79	40	5000	0	12	Baby4	0.2	Baby5
6	2.6	23.76	10	3000	0	3	Baby5	0.1	Baby6

This data hiding approach was first proposed by our group in 2007 [9] where the readers may find some detailed introductions. The data, a binary sequence, is hided in the image by modifying the magnitude in the transform domain.

When hiding the data, we first define a threshold T. Then from the beginning of the image, say the top left, each magnitude x is modified as follows.

$$x = \begin{cases} x & , & if \;\; x < T \\ x + b & , & if \;\; x = T \\ x + 1 & , & if \;\; x > T \end{cases} \qquad (8)$$

Where b is one of the information bit to be hided. If there are still data bits left when all the magnitudes have been scanned, we enlarge the threshold T and perform the data hiding process again. This iteration may be repeated until all the data bits can embedded into the image.

Now let's introduce the four optimal threshold parameters in Tables 1 and 2, namely T, TF, TL and TR. In the multiple circles embedding scheme the input image is different in each pass. So we need to re-choose the four parameters during new the data hiding process.

(a) The optimal magnitude threshold T: the threshold that is corresponding to the highest PSNR given the data to be embedded.

(b) The optimal fluctuation threshold T_F, defining the image regions by surrounding neighbors, which are comparatively smoother than the others. Hiding data into the smooth image region will make the highest PSNR. The optimal context threshold

(c) The optimal left and right grayscale threshold T_L and T_R: Before data hiding, we shrink the histogram of image, such that the grayscale range is within after data hiding. In consequence, not only optimal result is obtained, but also the overflow/underflow problem can be effectively relieved.

From Fig. 6 it can be observed that our employed lossless data hiding method is able to embed more data bits, and meanwhile the PSNR is much larger than the prior arts [3, 6].
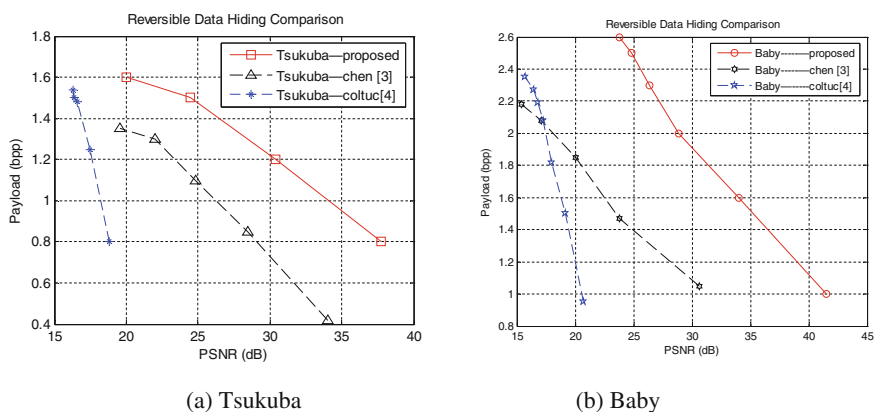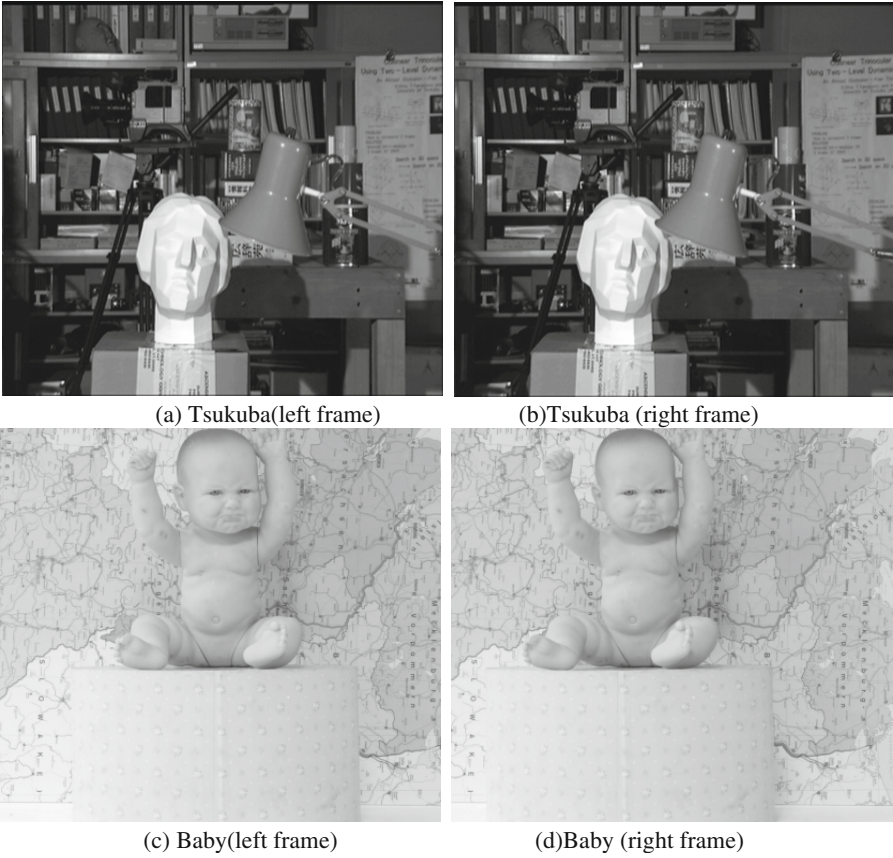

(a) Tsukuba   (b) Baby

Fig. 6. PSNR vs. Payload for the test images of Tsukuba and Baby (see Fig. 7).

(a) Tsukuba(left frame)   (b)Tsukuba (right frame)

(c) Baby(left frame)   (d)Baby (right frame)

Fig. 7. Test images used in this paper

The marked stereo image with high visual quality is favorable for the applications that stereo image decoding is unavailable. For instance, the users of 3D television can watch the 2D video directly when they lack of the decoder for 3D signal.

6 Stereo Image Reconstruction

As shown in Fig. 1, if decoder is available users can obtain the stereo image by decoding (otherwise, they can only watch the marked two-dimensional image). The decoding process is given as follows:

- Step 1: Using the data extracting method provided by [2], we obtain the compressed residual image cr, record information and visual difference value P. In addition, the original right frame R is also recovered meanwhile.
- Step 2: Decompress cr by means of JPEG2000 to obtain the residual image mr'. Decoding the record information by mean of Arithmetic coding algorithm in [7].
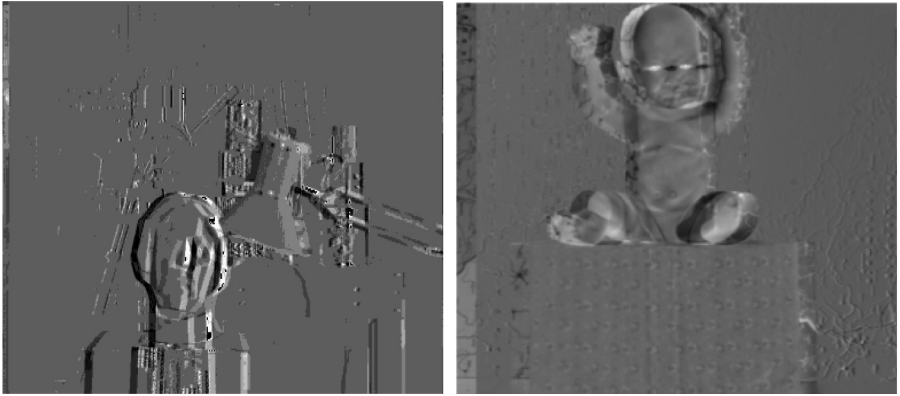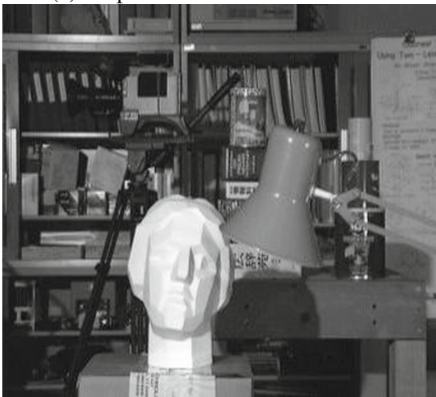
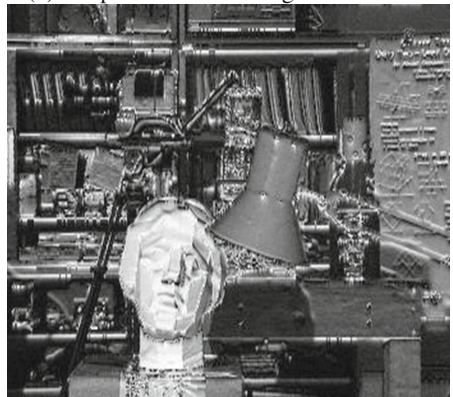**Fig. 8.** The Residual Image
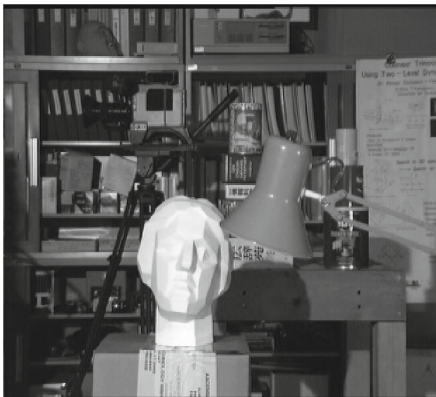
(a) Proposed reconstructed left frame
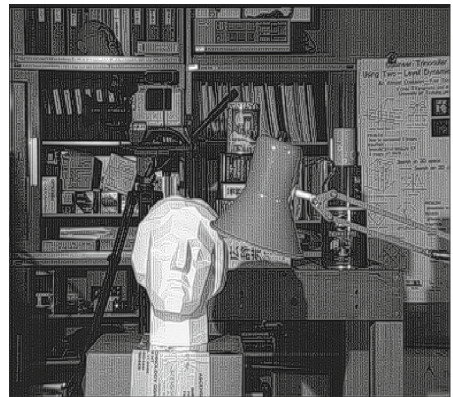
(b) Proposed embedded right frame
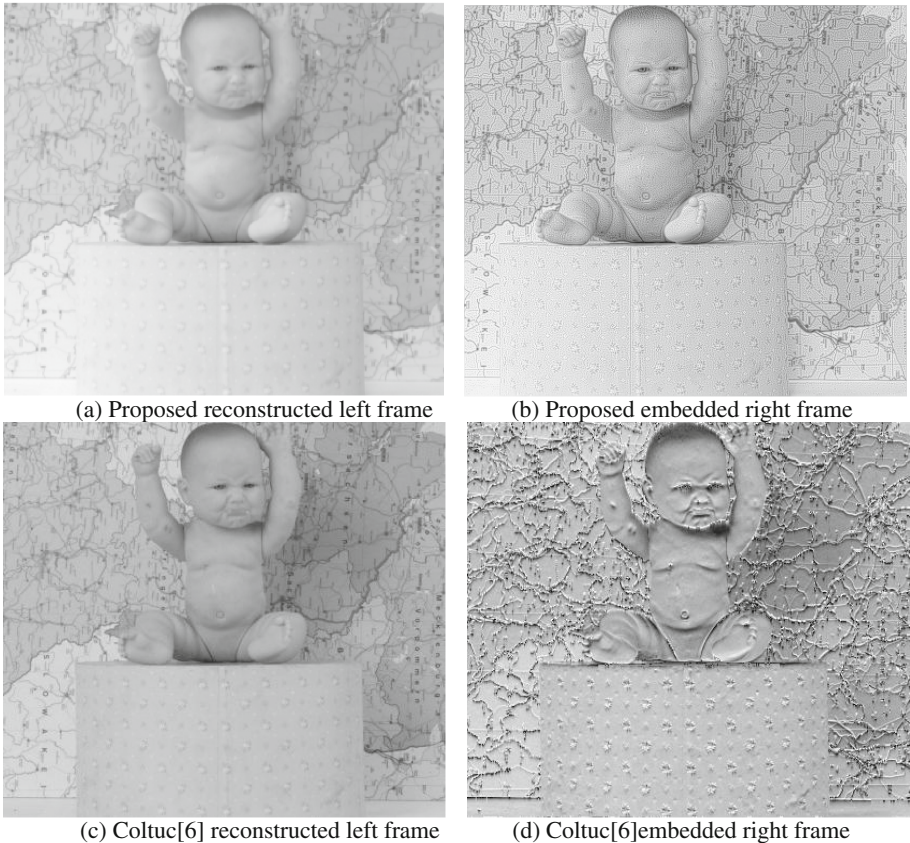
(c) Coltuc [6] reconstructed left frame

(d) Coltuc[6] embedded right frame

Fig. 9. Test results of Tsukuba

- Step 3: Modifying mr' to obtain correlation matrix mr. According to Eq. (7), for the pixels in mr' the coordinates of which are not given in record information, we subtract 128 from their values. For the pixels in mr' the coordinates of which are given in record information and its gray value less than 128, we multiply their values by −1 and minus 129. For the pixels in mr' the coordinates of which are given in record information and its gray value more than 128, we use 255 minus its gray value and add 128.
- Step 4: Reconstructing the right frame L' via the right frame R and the correlation information mr. According to Eq. (4), before adding with the right frame R, we left translate the correlation information with and offset of P pixel. The columns translated beyond the frame are added to the first column of R.

7   Experimental Results

We test our proposed method by means of two standard stereo images, namely Tsukuba (384 × 288 in size) and Baby (413 × 370 in size) as shown in Fig. 3.

(a) Proposed reconstructed left frame   (b) Proposed embedded right frame

(c) Coltuc[6] reconstructed left frame   (d) Coltuc[6]embedded right frame

Fig. 10. Test results of Baby

The residual images of Tsukuba and Baby derived from the disparity of two frames (refer to Sect. 2) are given in Fig. 8.

In order for good visual quality of the reconstructed image, we wish the loss JPEG2000 compression performed on residual image could be as slightly as possible. And hence, the data hiding capacity should be large enough to store the compressed residual image. As presented in Fig. 6, the employed reversible data hiding method is able to embed more data under the same PSNR in comparison with the method in [1, 8].

Figures 9 and 10 present the frames at the decoding end of Tsukuba and Baby, respectively. Each figure includes the marked right frame and the reconstructed left frame. In addition, the results of Coltuc's method are also given. It is easy to observe the advantage of our proposed coding method in visual quality.

Table 3 presents the comparison result of the proposed stereo image coding method with three state-of-the-art ones in terms of payload vs. PSNR. It can be observed that the proposed method is able to reconstruct the left frames of the both stereo images with the largest PSNR. This result can also explain the good visual quality of the decoded stereo images illustrated in Figs. 9 and 10.

Table 3. Comparisons of stereo image coding methods on Payload vs. PSNR

Method	Tsukuba			Baby		
	Payload (bpp)	Embedded right frame PSNR (dB)	Reconstructed left frame PSNR (dB)	Payload (bpp)	Embedded right frame PSNR (dB)	Reconstructed left frame PSNR (dB)
Proposed	1.6	20.01	44.63	2.56	23.76	49.96
Chen [3]	1.35	19.59	42.72	2.18	15.44	48.96
Coltuc [4]	1.55	16.3	38.5	2.4	15.8	39.0
Coltuc [6]	1.55	16.3	44	2.4	15.8	41.5

8   Discussions and Conclusions

1. This paper proposed a stereo image encoding/decoding method, which is able to hide the stereo information into one frame and only this frame needs to be transmitted. As a result, the transmission efficiency is doubled and the storage cost is saved greatly. In addition, the visual quality of the marked image is improved in comparison with the prior arts. Because to watch the marked image directly without decoding is visually acceptable, the stereo image playback system is compatible with the 2D image system.

2. The right frame can be recovered losslessly and the left frame can be reconstructed with high quality. For example, the PSNR of reconstructed of left frame in proposed method reaches either 44.63 dB (Tsukuba) or 49.96 dB (Baby) respectively. It is about 2 dB (Tsukuba) or 1 dB (Baby) proposed higher than that of prior-arts, see Table 3.

3. We conclude as follows why our decoded stereo image is with better visual quality than the prior arts:

(a) The compressed residual image is embedded by means of histogram-pair based data hiding algorithm. Comparing with Tian's DE-based algorithm [1], the histogram-pair based algorithm is with higher PSNR and larger embedding capacity. Refer to Table 3, the embedding capacity is 1.6 bpp when PSNR is 20.01 dB for the proposed method marking Tsukuba image, which improves 0.25 bpp comparing the best prior art under similar PSNR value. And the improvement for Baby image is even more obvious. Furthermore, owing to the advantage of the proposed histogram-pair based data hiding method, we can obtain the better visual quality than the prior arts under the same PSNR value (refer to Fig. 10(a) and (c)).

(b) The residual error image [0, 255] is generated by labeling scheme proposed from residual error matrix lossless (before JPEG2000 loss compression). The residual error matrix [−255,255] is obtained lossless in proposed scheme instead of obtained loss by downsize images with gray level [−127, 127] in prior-arts.

4. The proposed method is with higher stereo image coding speed than the prior arts owing to the use of frame-wise disparity algorithm. The algorithm simplifies the computation and satisfies the requirement of real time applications. And, more important, higher quality of left frame than that in prior-arts.

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