Stereo Matching Based Stereo Image Watermarking for Tamper Detection and Recovery

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Abstract

Digital watermarking is an effective way for authentication of stereo images when they are transmitted over networks. Since the left and right images of a stereo image pair are not independent but similar to each other, their watermarking design should be different from that of mono-images. This paper thus proposes a stereo matching based stereo image watermarking scheme for tamper detection and recovery. One-to-one mappings between left and right image blocks are established, and tamper detection bits generated from each block and the recovery bits of the mapped block are embedded back to the block itself. To keep the consistency between left and right images, a stereo image pair is usually tampered symmetrically. That is, the tampered areas in left and right images are similar to each other, thus the combination of tamper detection results of left and right images can facilitate more accurate tamper detection results. In general, a tampered block in one image of stereo image pair can be recovered with the recovery bits embedded in its mapped block in the other view. However, if the mapped block is also tampered, stereo matching based method is employed to recover the tampered block. Our experimental results show that the proposed tamper detection scheme can identify the tampered blocks with the probability of almost 1 if the stereo image is modified symmetrically. Moreover, the proposed scheme is able to recover a view of stereo images altered 100% which may even confuse the human eyes.

Keywords: Three-dimensional television; Stereo image watermarking; Tamper detection; Stereo matching.

1. Introduction

Three-dimensional television (3DTV) is expected to be the next revolution in the advancement of television, and stereo images displayed on 3DTV are expected to increase visual impacts and heighten the sense of presence for viewers[1]. When stereo images are published on the Internet, they may be tampered for some illegal purposes with image processing tools without permission. This kind of behaviors undermines the integrity and authenticity of stereo images. Watermarking is considered as an efficient solution to address this problem. Some watermarking schemes had been designed to detect and locate tampered areas for image authentication[2,3]. Moreover, tampered areas are expected to be recovered based on recovery information of the watermarked image. Lin et al. presented a typical fragile watermarking scheme for image tamper detection and recovery with a hierarchical structure[4]. Lee et al. proposed a dual watermarking scheme to improve Lin's scheme[5]. Two copies of watermark provide two chances for block recovery. However, three least significant bits (LSB) are employed to embed watermark, and the imperception of watermarked images is weak. Many other watermarking schemes were proposed for improving the tamper detection and recovery[6,7,8]. But these schemes are mainly designed for mono-images.

For the purpose of stereo image watermarking, stereo data can be applied in two ways. One is to consider the image pair as two independent images. Huang et al. have proposed two methods in this direction: discrete cosine transform (DCT) and discrete wavelet transform (DWT) based stereo image watermarking[9,10], without considering relationships between stereo image pairs. This kind of methods does not guarantee a success in stereoscopic image processing[11], such as disparity estimation. The other way utilizes the relationships between left and right images to embed watermark. Chammem et al. improved Huang's schemes and embedded the watermark into disparity map directly[11]. Moreover, depth image obtained from stereo image can also be used for stereo image watermarking[12]. The above schemes are often used for copyright protection.

For stereo images, stereo matching[13] is its inherent relationship between left and right images. Therefore, the stereo matched pair can be used for tamper recovery if one block is tampered and the other is not. Moreover, if a stereo image is modified symmetrically, its left and right images should be pasted or cropped with the same objects to keep the stereo matching. This feature is helpful to heighten the accuracy of tamper detection. In this paper, a stereo matching based stereo image watermarking scheme is presented for stereo tamper detection and recovery. The rest of paper is organized as follows. The tamper of stereo images is described in Section 2. Section 3 describes the proposed scheme in detail, and a series of experimental results are given and analyzed in Section 4. Finally, section 5 concludes the paper.

2. Tamper of stereo images with stereo matching

A stereo image is captured with a dual camera system. We define stereo matching as $I_l(x+d_1,y+d_2)=I_r(x,y)$ ideally, where I_l and I_r are intensities of pixels in left and right images respectively, x and y are coordinate of pixel in an image, d_1 and d_2 are the horizontal and vertical disparities.

The tamper of stereo image is different from that of mono-image. If stereo images are modified, inter-view relationships between its left and right images should be taken into account. Otherwise, the tamper is easily discovered by human visions. We formulize tampered pixels, and let T_l and T_r be the coordinate sets of tampered pixels in left and right images, respectively.

$$T_l = T_{lc} \cup T_{ln},\ T_r = T_{rc} \cup T_{rn} \tag{1}$$

T_{lc}, T_{ln}, T_{rc} and T_{rn} are defined by

$$T_{lc} = \{(x,y) \mid I_l(x,y) = I_r(x-d_1, y-d_2),\ m_r(x-d_1, y-d_2) = -1, m_l(x,y) = -1, d_1, d_2 \in \mathrm{R}\}$$

$$T_{ln} = \{(x,y) \mid I_l(x,y) = I_r(x-d_1, y-d_2),\ m_r(x-d_1, y-d_2) \neq -1, m_l(x,y) = -1, d_1, d_2 \in \mathrm{R}\}$$

$$T_{rc} = \{(x,y) \mid I_l(x+d_1, y+d_2) = I_r(x,y),\ m_l(x+d_1, y+d_2) = -1, m_r(x,y) = -1, d_1, d_2 \in \mathrm{R}\}$$

$$T_{rn} = \{(x,y) \mid I_l(x+d_1, y+d_2) = I_r(x,y),\ m_l(x+d_1, y+d_2) \neq -1, m_r(x,y) = -1, d_1, d_2 \in \mathrm{R}\}$$

where the value -1 of m_l or m_r indicates the corresponding pixels in left or right images are detected as tampered pixels.

Tamper of stereo images can be classified as symmetrical and asymmetrical modifications. If T_l is different from T_r, stereo image is asymmetrically tampered. It is easy to discover asymmetrical modification of stereo image visually via comparing the left image with the right image. But for symmetrical modifications, T_l is usually equal to T_r, that is to say, the tampered areas in left and right images are similar to each other. This feature gives us a chance to improve the accuracy of tamper detection through combining tamper detection results of left and right images.

In Eq.(1), pixels in sets T_{ln} and T_{rn} can be recovered with their corresponding pixels in the other view of stereo pair. But for pixels in sets T_{lc} and T_{rc}, since their corresponding pixels are also tampered, the stereo matching based recovery is unable to be implemented. However, if the information on these areas is included in watermark, the recovery will not be impossible.

3. The proposed scheme

The proposed stereo matching based stereo image watermarking scheme composes of three parts, that is, watermark embedding, tamper detection and recovery.

3.1. *Watermark embedding for stereo image*

Let left and right images be of size $N_1 \times N_2$, where N_1 and N_2 are assumed to be a multiple of four. Each pixel's intensity is represented by 8 bits, denoted by $a_1,a_2,\ldots,a_8$, and a_1 is the most significant bit, while a_7 and a_8 are two less significant bits. The left and right images of a stereo image pair are divided into non-overlapping blocks with the size of 4×4, and each block of each image is assigned a unique and consecutive integer $x\in\{1, 2, 3\ldots,L\}$ from left to right and top to bottom, where $L=(N_1/4)\times(N_2/4)$.

Firstly, each block in one view of a stereo image pair is mapped to a unique block in the other view for preserving its own intensity information. The one-to-one mapping is defined as

$$i' = L - (k \times i \bmod L) + 1 \qquad (2)$$

where i is the block number in left image, and i' is the block number in right image. Thus, block $B_{l,i}$ in the left image and block $B_{r,i'}$ in the right image are the so called mapped block with each other. k is a secret key to encrypt watermark information and should be 1 or a prime between 2 to L-1 to forbid many-to-one mapping.

In watermark embedding procedure, two LSBs of each pixel are replaced with tamper detection watermark and recovery watermark. Thus for 4×4 block the watermark capacity of each block is 32 bits, among which 4 bits denoted as v_1, v_2, v_3 and v_4 are used for tamper detection of the carrier itself, while the other 28 bits are used for tamper recovery of the mapped block. The procedure of watermark generation and embedding is described as follows.

Step-a1. Calculate standard deviation of each block of the left and right images, and further calculate the average of the standard deviations, denoted as avg_{SDL} and avg_{SDR}, for left image and right image respectively. Both avg_{SDL} and avg_{SDR} are persevered as secret keys in watermark extraction process. If standard deviation of a block is greater than the average standard deviation of the image it belongs to, v_1 of the block is set to 1, otherwise, v_1 is 0.

Step-a2. For a block to be processed, it is further divided into 2×2 sub-blocks, and the sub-block, whose standard deviation is nearest to the average of standard deviations of sub-blocks in this block, is named as *average sub-block*. v_2 and v_3 are related to position of the *average sub-block*. Here, the position of left-top sub-block in each block is coded as "00", and the other three sub-blocks are assigned with "01", "10" and "11", respectively. Hence, we can use v_2 to record the first bit of the position and v_3 for the second bit.

Step-a3. *Average sub-block* has four pixels denoted as I_1, I_2, I_3 and I_4, and they are marked as 0, 1, 2, and 3, respectively. In each block, v_1, v_2, and v_3 are summed to get a new value z, which can be 0, 1, 2 or 3 and determines which pixel in the *average sub-block* is corresponding to v_4

$$v_4 = I_{z+1} \bmod 2 \qquad (3)$$

Step-a4. The other 28 bits watermark is generated from the mapped block, used for recovery of the mapped block. The mapped block is also further divided into non-overlapping sub-blocks with the size of 2×2. The average intensities of the four sub-blocks are calculated and denoted as avg_1, avg_2, avg_3 and avg_4, respectively. The recovery bits of the mapped block are obtained by truncating one LSB of avg_1, avg_2, avg_3 and avg_4, as illustrated in Fig. 1, where $I_{m,n}$ denotes the n^{th} pixel in the m^{th} sub-block of each block, and $1\le m,n\le 4$.

After block watermark being generated, 32 bits are embedded into the corresponding positions of each block, as depicted in Table 1.

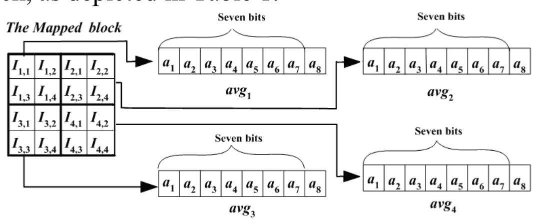


Fig. 1. Generation of 28 recovery bits from the mapped block.

Table 1. Embedding position of 32 bits watermark.

pixel	a_8	a_7	pixel	a_8	a_7
$I_{1,1}$	v_1	$avg_2\_a_6$	$I_{3,1}$	$avg_1\_a_5$	$avg_3\_a_1$
$I_{1,2}$	v_2	$avg_2\_a_7$	$I_{3,2}$	$avg_1\_a_6$	$avg_4\_a_1$
$I_{1,3}$	v_3	$avg_3\_a_1$	$I_{3,3}$	$avg_1\_a_7$	$avg_4\_a_2$
$I_{1,4}$	v_4	$avg_3\_a_2$	$I_{3,4}$	$avg_2\_a_1$	$avg_4\_a_3$
$I_{2,1}$	$avg_1\_a_1$	$avg_3\_a_3$	$I_{4,1}$	$avg_2\_a_2$	$avg_4\_a_4$
$I_{2,2}$	$avg_1\_a_2$	$avg_3\_a_4$	$I_{4,2}$	$avg_2\_a_3$	$avg_4\_a_5$
$I_{2,3}$	$avg_1\_a_3$	$avg_3\_a_5$	$I_{4,3}$	$avg_2\_a_4$	$avg_4\_a_6$
$I_{2,4}$	$avg_1\_a_4$	$avg_3\_a_6$	$I_{4,4}$	$avg_2\_a_5$	$avg_4\_a_7$

3.2. *Detection of tampered blocks*

The detection of tampered block is implemented in the following three levels.

The first level of tamper detection is implemented with the embedded watermark. It is quite similar to block watermark embedding, described as follows.

Step-b1. Firstly, the left and right images are also divided into non-overlapping 4×4 blocks. For each 4×4 block, two LSBs of each pixel in the block are extracted. Four bits used for tamper detection are denoted as v_1, v_2, v_3 and v_4. The other 28 bits can be used to generate the average intensity of each 2×2 sub-blocks of the block by appending the 7 bits intensity with one zero, as illustrated in Fig. 1. The appended 8 bits intensities are denoted as avg'_1, avg'_2, avg'_3 and avg'_4, respectively.

Step-b2. Set two LSBs of each pixel in the block to zero. v'_1, v'_2, v'_3 and v'_4 are calculated in the same way as the generation of 4 bits for tamper detection in subsection 3.1. In this process, the secret keys avg_{SDL} and avg_{SDR} are employed to compute v'_1.

Step-b3. The extracted v''_1, v''_2, v''_3 and v''_4 are compared with the calculated v'_1, v'_2, v'_3 and v'_4, respectively. If any pair is not equal with each other, the block is identified as tampered block and marked as erroneous, otherwise, it is a valid block.

At the second level of tamper detection, the isolated valid block, which is surrounded by erroneous blocks, will be remarked as erroneous block. As shown in Fig. 2, if at least two neighbors of a valid block are marked as erroneous, the valid block will be marked as erroneous. This process will repeat until no such cases as shown in Fig.2 are found.

For a stereo image pair, normally the modification is symmetrical, and as a result, the detected tampered areas in left and right images should also be similar to each other. Thus, the combination of tamper detection results with respect to left and right images can facilitate to achieve more accurate tamper detection. Based on the point of view, at the third level of tamper detection, the sizes of tampered areas in the left and right images are compared. If the difference between the sizes of tampered areas is less than a predefined threshold and the coordinates of the tampered areas in the left and right image satisfy disparity constraint, the modification is considered to be symmetric, and the corresponding tamper detection results with respect to left and right images will be combined. Let $T_{l,n}$ and $T_{r,n}$ be the n^{th} pair of tampered areas in left and right images, respectively, $T'_{l,n}$ be the shift of $T_{l,n}$ according to the disparity between the left and right image, then the combination of $T'_{l,n}$ and $T_{r,n}$ is defined as follows and regarded as the final result of the n^{th} tampered area

$$T_{o,n} = T'_{l,n} \cup T_{r,n} \tag{4}$$

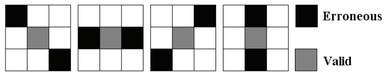


Fig. 2. The 3×3 block-neighborhood of valid blocks.

3.3. *Tampered block recovery*

In the proposed scheme, a tampered area can be recovered through watermark based recovery, stereo matching based recovery and spatial interpolation with its neighbors. The first level of recovery is based on the watermark information embedded in the mapped block of the tampered block. One-to-one mappings are obtained between blocks of left and right images via the secret key k according to Eq. (2). For a tampered block, if its mapped block in the other view is tampered too, the tampered block will be recovered in the next level. Otherwise, it will be recovered as follows.

Suppose $B_{l,i}$ is a tampered block in the left image, and its mapped block $B_{r,i'}$ is valid in the right image. Therefore avg'_1, avg'_2, avg'_3 and avg'_4 with respect to $B_{l,i}$ can be obtained from $B_{r,i'}$ as described, and pixels of each 2×2 sub-blocks of $B_{l,i}$ will be recovered with the four averages, respectively. This step is repeated until no more tampered blocks in the left image can be recovered with this manner. The tampered blocks in the right image will be recovered in the same way.

If all tampered blocks are recovered at the first level of recovery, the recovery will be finished. However, if there still remain blocks not being recovered, stereo matching based method will be implemented. In fact, the stereo matching based recovery method can only recover pixels in the sets of T_{ln} and T_{rn} in Eq.(1). Stereo matching is implemented to search the horizontal disparity d_1 and vertical disparity d_2 of each tampered area of the stereo image, so as to recover the tempered area with its corresponding area in the other view. However, since the information on the tampered area itself is not known, the stereo matching can not be done directly for the tampered area. Fortunately, there exist spatial correlations among neighboring blocks, as well as their disparities. Thus, the disparity of tampered block can be estimated with its valid neighboring blocks. In order to reduce time consuming, the image blocks in the same tampered area is supposed to have the same d_1 and d_2. In this paper, a tampered block in a tampered area satisfying any of situations shown in Fig. 3 is looked for, so that its three valid neighboring blocks can be used to implement the stereo matching. Sum of squared difference (SDD) is used as the criterion, and the disparity vector achieving minimum SDD is supposed to be the best one for the tampered block, as well as other tempered blocks in the same tampered area.

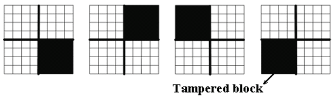


Fig. 3. The representative tampered block selected for stereo matching based recovery.

(a) “Laundry” (b) “Art” (c)“ Alt Moabit ”

Fig. 4. Left images of three original stereo images.

After the above two levels of recovery, sometimes there may still remain a few tampered blocks not to be recovered. For these tampered blocks, the third level of recovery which is in fact the interpolation within the image itself is utilized.

At the third level of recovery, 3×3 block-neighborhood of a tampered block is employed. Average intensity of pixels in valid neighboring blocks is computed and used as the intensity of pixels in the tampered block, until all remained tampered blocks in left and right images are recovered.

3.4. *The algorithm*

Watermark embedding, tamper detection and recovery are summarized as two algorithms. Watermark embedding is shown in Algorithm 1.

Algorithm 1 Watermarking embedding

Input: I_l, I_r (Original left and right images) and k

Output: $I_{w,l}$ and $I_{w,r}$ (Watermarked left and right images)

Set a_7 and a_8 of each pixel to 0, and I_l and I_r are divided into blocks

For i=1 to L

$i' \fallingdotseq L-(k\times i \bmod L)+1$

$(v_1, v_2, v_3, v_4) = f_d(B_{l,i})$, $(avg_1, avg_2, avg_3, avg_4) = f_d(B_{l,i})$, $(v_1, v_2, v_3, v_4)' = f_r(B_{r,i'})$, $(avg_1, avg_2, avg_3, avg_4)' = f_r(B_{r,i'})$

a_7 and a_8 of each pixel in $B_{l,i}$ are replaced by (v_1, v_2, v_3, v_4) and 28 bits from $(avg_1, avg_2, avg_3, avg_4)'$ based on Table 1

a_7 and a_8 of each pixel in $B_{r,i'}$ are replaced by $(v_1, v_2, v_3, v_4)'$ and 28 bits from $(avg_1, avg_2, avg_3, avg_4)$ based on Table 1

End for

$f_d(\cdot)$ and $f_r(\cdot)$ computes four tamper detection bits and four average intensities of sub-blocks, respectively, using the method in subsection 3.1. The watermarked stereo image may be counterfeited, and tamper detection and recovery are summarized as in Algorithm 2.

Algorithm 2 Tamper detection and recovery

Input: $I_{t,l}$, $I_{t,r}$ (Counterfeit left and right images), and k

Output: $I_{t,l}$, $I_{t,r}$ (Recovered left and right images)

$I_{t,l}$ and $I_{t,r}$ are divided into blocks, respectively

For i=1 to L

$(v''_1, v''_2, v''_3, v''_4) = f_{ed}(B_{l,i})$, $(v''_1, v''_2, v''_3, v''_4)' = f_{ed}(B_{r,i})$

set a_7 and a_8 of each pixel in $B_{l,i}$ and $B_{r,i}$ to 0, and $(v'_1, v'_2, v'_3, v'_4) = f_d(B_{l,i})$ and $(v'_1, v'_2, v'_3, v'_4)' = f_d(B_{r,i})$

if $(v''_1, v''_2, v''_3, v''_4) \neq (v'_1, v'_2, v'_3, v'_4)$

$F_{l,i}$=1 // block i in left image is tampered

if $(v''_1, v''_2, v''_3, v''_4)' \neq (v'_1, v'_2, v'_3, v'_4)'$

$F_{r,i}$=1 // block i in right image is tampered

End for

For i= 1 to L

if $F_{l,i}$ or $F_{r,i}$ satisfying Fig.1

$F_{l,i}$ or $F_{r,i}$ =1

End for

$T_{l,n}$ $T_{r,n}$ are computed from F_l and F_r, respectively, and combine them using Eq. (4) and update F_l and F_r

For i= 1 to L

$i' \fallingdotseq L-(k\times i \bmod L)+1$

if $F_{l,i}$ =1

if $F_{r,i'} \neq 1$

$(avg'_1, avg'_2, avg'_3$ and $avg'_4) = f_{er}(B_{r,i'})$, and recover $B_{l,i}$

else

if $F_{r,i'}$ =1

$(avg'_1, avg'_2, avg'_3$ and $avg'_4) \fallingdotseq f_{er}(B_{l,i})$, and recover $B_{r,i'}$

End for

For i= 1 to L

if $F_{l,i}$ =1

$\langle d_1, d_2 \rangle = SDD(B_{l,i})$, and recover $B_{l,i}$ using matched blocks

if $F_{r,i}$ =1

$\langle d_1, d_2 \rangle \fallingdotseq SDD(B_{r,i})$, and recover $B_{r,i}$ using matched blocks

End for

For i=1 to L

if $F_{l,i}$ =1 or $F_{r,i}$ =1

spatial interpolation is used to recover $B_{l,i}$ or $B_{r,i}$

End for

$f_{ed}(\cdot)$ and $f_{er}(\cdot)$ extract tamper detection and recovery bits, respectively, and $SDD(\cdot)$ returns valid disparity, which is used to recover tamper in second level of recovery.

Table 2. PSNRs of the watermarked images. [unit: dB]

Schemes	Laundry		Art		Alt Moabit	
Proposed	44.2	44.2	44.3	44.2	44.4	44.4
Lin’s	44.4	44.4	44.2	44.3	44.2	44.2
Lee’s	40.2	40.3	40.1	39.9	40.3	40.4

Table 3. PSNR comparison between stereo matching and interpolation based recoveries. [unit: dB]

Area	right block T_2		left-bottom block T_3	
Stereo matching	32.0	33.3	29.9	28.2
Block-neighborhood	31.7	32.9	29.7	28.1

4. Experimental results and discussions

To test the effectiveness of the proposed scheme on tamper detection and recovery, three stereo images including the first frames of "Laundry" and "Art", which are with the size of 640×480, and "Alt Moabit" with the size of 1024×768, are used in the experiments. Left images of these stereo pairs are shown in Fig. 4. Peak signal-to-noise ratio (PSNR) is employed to evaluate the quality of watermarked images, as shown in Table 2. For one stereo pair, the first number is with respect to the left and the other is PSNR of the right. Obviously, all PSNR*s* of the proposed scheme are higher than 44dB, which means that the transparency of the embedded watermark is satisfied for applications.

In the experiments, Lin's[4] and Lee's[5] schemes are also extended to stereo images where the stereo image is considered as two independent images. Table 2 also gives PSNRs of Lin's and Lee's schemes. It is seen that Lee's scheme is inferior to the proposed scheme in PSNR due to three bits of each pixel used for embedding watermark. The results of Lin's scheme are similar to that of the proposed scheme.

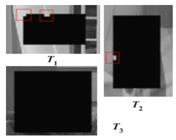
Stereo images are often tampered symmetrically. In the following experiments, the left and right images are tampered with the same things, but the locations in the two views may be slightly different due to disparity. In Figs. 5(a) and 5(b), three different areas are cropped from "Laundry". The left-top block, right block and left-bottom block are referred as T_1, T_2 and T_3 hereafter. Figs. 5(c) and 5(d) show the tamper detection results after the first two levels of tamper detection in which the black blocks mark the erroneous blocks. However, a few regions marked with red rectangles are not identified by the first two levels of tamper detection. But they are successfully detected after the third level of tamper detection, as shown in Figs. 5(e) and 5(f), where the tamper detection rate P_a is 100%.

Figs. 5(g) and 5(h) give recovery results of left and right images after the watermark based tamper recovery. It is noticed that there are some blocks not recovered. But after the stereo matching based tamper recovery, all tampered blocks are recovered, and the recovery are imperceptible, as shown in Figs. 5(i) and 5(j).

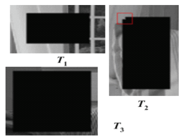
To test the performance of stereo matching based recovery, it is replaced by the interpolation based recovery in the second level of recovery. Figs. 6(a) and 6(b) give the recovery results of the interpolation based recovery. The block effects in Figs. 6(a) and 6(b) are easily noticed compared with Figs. 5(i) and 5(j). In fact, the block effect is hardly to be avoided especially at texture regions or edge regions, since the tampered block is recovered with its neighboring valid block in interpolation based recovery. In the proposed scheme, interpolation based recovery will be triggered only if both the watermark based and stereo matching based recovers fail to recover the tampered block. Thus the probability of using interpolation based recovery is very low, and the sizes of the remained tampered areas are also small, so that the block effect may be suppressed to some extent. PSNR is employed for comparison as well and the results are given in Table 3. In the table, the right block and left-bottom block refer to the two cropped blocks T_2 and T_3 in Fig. 5. The left-top block T_1 in Fig. 5 is not included in Table 3 since it does not need the second level of recovery. Table 3 indicates that the stereo matching based recovery is superior to interpolation based recovery.


(a) Tampered left image

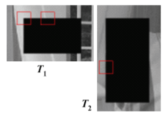

(b) Tampered right image



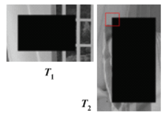
(c) Tamper detection results of left image after the first two level detections



(d) Tamper detection results of right image after the first two level detections



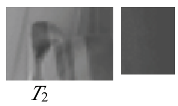
(e) Tamper detection results of left image after the third level detection



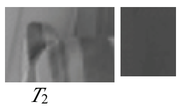
(f) Tamper detection results of right image after the third level detection


(g) Watermark based recovery of left image


(h) Watermark based recovery of right image

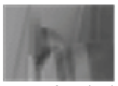


(i) Local recovery results of left image after stereo matching based recovery



(j) Local recovery results of right image after stereo matching based recovery

Fig. 5. Tamper detection and recovery of "Laundry".


(a) Recovery of T_2 in left image

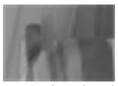

(b) Recovery of T_2 in right image

Fig. 6. Local recovery results of T_2 in "Laundry" obtained with interpolation based recovery.

In reality, stereo images are sometimes modified with minor areas and cannot be discovered visually. In "Art", an extra "pen" is pasted as shown in Figs. 7(a) and 7(b), and two extra cameras and one "transformer logo" are pasted on "Alt Mobait" as shown in Figs. 8(a) and 8(b). The tampered blocks are almost detected after the three levels of tamper detection as shown in Figs. 7(c), 7(d), 8(c) and 8(d), where the tampered areas are marked as the white. They are imperceptibly recovered as shown in Figs. 7(e), 7(f), 8(e) and 8(f).

The capabilities in tamper detection and recovery of the proposed scheme are also compared with Lin's and Lee's schemes. Table 4 shows that the most of tamper detection rate P_a for the left and right images of the proposed scheme approach to 100%. Although for "Alt Moabit" and "Art" some P_a is not 100%, but still better than that of Lin's and Lee's schemes. Especially P_a of Lee's scheme is 6.7 for right image of "Alt Moabit", which means that the scheme is unstable for different tamper of images. PSNR of the recovered image relative to the tampered area is utilized for evaluating the quality of recovery. For "Art" and "Alt Moabit", the recovery can be achieved with the watermark based recovery, while for "Laundry", the first two levels of recovery is needed. As shown in Table 5, PSNRs of the proposed scheme with respect to "Art" are the best with around 35dB, which is much higher than that of "Alt Moabit". The reason is that the tampered areas of "Art" belong to smooth regions, while that of "Alt Moabit" are texture regions. For these two stereo images, the proposed scheme is comparable with the Lin's but better than the Lee's. For "Laundry", the proposed scheme achieves better results compared with both of the others.

Although stereo image pairs are usually modified symmetrically, in order to test the tamper detection and recovery performance of a watermarking scheme, a stereo image is supposed that one of its views is replaced with another image with the same size. In this case, people will be confused with which image is the original, and the watermarking schemes in which left and right images are considered as two independent ones are unable to recovery the replaced view since it is 100% altered. By contrast, the proposed scheme is competent for such case. Take the watermarked "Alt Moabit" as an example, suppose its left image is replaced with "Scenery" and the left image of "Book Arrival" with the same size as shown in Figs. 9. For asymmetrical modification, only the first two levels of tamper detection are used to identify the tampered areas. Table 6 shows that nearly 99% tampered blocks are identified with the proposed tamper detection method. The recovered left image of "Alt Moabit" is with PSNR of around 31.9dB.

Table 4. Tamper detection rate P_a after final tamper detection with different watermarking schemes. [percent: %]

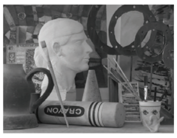
Stereo Image	Laundry		Art		Alt Moabit	
Proposed	100	100	99.8	100	99.0	100
Lin's	99.7	99.8	99.6	98.9	98.1	98.2
Lee's	99.7	99.7	98.2	98.5	98.6	6.7

Table 5. PSNRs of image recovered with different watermarking schemes. [unit: dB]

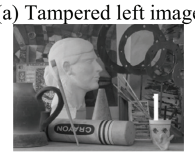
Stereo Image	Laundry		Art		Alt Moabit	
Proposed	30.4	31.6	35.5	36.9	30.3	31.1
Lin's	27.9	26.6	35.7	35.6	30.1	30.7
Lee's	27.6	27.1	31.2	30.7	28.2	28.8

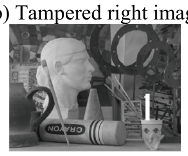
Table 6. P_a after two levels of tamper detection.

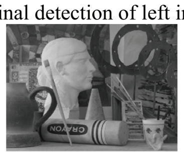
Replacements	"scenery"	"book arrivals"
After the level-one	93.8%	93.9%
After the level-two	99.7%	99.9%


(a) Tampered left image


(b) Tampered right image


(c) Final detection of left image


(d) Final detection of right image


(e) Final recovery of left image

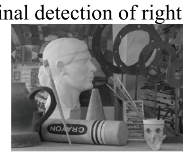
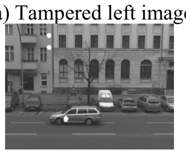

(f) Final recovery of right image

Fig. 7. Recovery of the tampered "Art".


(a) Tampered left image


(b) Tampered right image


(c) Final detection of left image


(d) Final detection of right image


(e) Final recovery of left image


(f) Final recovery of right image

Fig. 8. Recovery of tampered “Alt Moabit”.


(a) “Scenery”

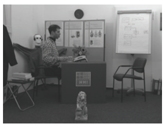

(b) “Book Arrival”

Fig. 9. The replacements of left image of “Alt Moabit”.

5. Conclusions

A stereo-matching-based stereo image watermarking scheme for tamper detection and recovery is proposed in this paper. Ordinary tamper detection results obtained from watermark detection are further refined through two levels of tamper detection. The combination of the matched identified tampered areas can improve the accuracy of temper detection nearly to 100% for left and right images. By establishing the mapping relationship and utilizing the inherent stereo matching relationship between left and right images, the proposed scheme achieves good results in tamper recovery, and is able to recover a view of the stereo image altered 100%, even though the alter images confuse the human eyes. Our future work will focus on exploring more relationships between the stereo image pair. For instance, stereo image can create depth information, which is an essential factor to determine region of interest. Thus, alterable bits of watermark can be allocated for different kinds of regions so as to design stereo image watermarking schemes with better performances.

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