Correlation-Based Model of Color Picture Watermarking against Random Geometric Distortion

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Abstract

Random geometric distortion is one of the most difficult kinds of image processing to survive and has been a noted problem in watermarking research. Previous methods for dealing with random geometric distortion, however, are accompanied by large computational overhead or by operational inconvenience. This paper therefore proposes a method based on embedding watermark patterns in two of the three color planes constituting a color picture so that these two planes have a specific correlation less subject to random geometric distortion. Experimental evaluations using StirMark confirmed that information of over 100 bits embedded in 256×256*-pixel pictures can be correctly detected without using searches or special patterns.*

1 Introduction

Digital watermarks on pictures must be able to survive geometric and nongeometric image processing operations. Watermarking robust to geometric image processing has been studied to develop various methods such as searching the picture for the embedded watermark [1] and using watermark patterns robust to the geometric distortions [2]. Random geometric distortion introduced by StirMark [3] is one of the most difficult kinds of geometric image processing for watermarks to survive and treating this operation required additional methods such as searching with the help of the original pictures [4] and learning the ways of distortions from training data [5]. The essential difficulty in treating random geometric distortion is the synchronization between the expected watermark pattern and the watermark embedded in the picture because parts of the embedded watermark are distorted in different ways.

The watermarking method for color still picture proposed in this paper is based on a principle different from those of the previous methods: watermarks are embedded in two of the three color planes (e.g., the R and G planes) and their detection is based on the correlation values between these two planes. The method is based on the fact that these two planes are distorted in the same way. Section 2 of this paper describes the basic idea of this method and Section 3 describes the actual method. Section 4 reports experimental evaluations confirming that the method can deal with random geometric distortion, and Section 5 concludes the paper.

2 Watermarking method correlating two constituent planes

The proposed method embeds synchronized PN sequences into two of the planes constituting a color picture (e.g., the R and G planes) and detects the sequences by correlating these two planes. Because the two planes of the color picture are distorted in the same way, the PN sequence embedded in one plane is synchronized with that embedded in the other even after random geometric distortion. Thus the detection based on their correlation works without searches or special patterns.

2.1 Terminology

The d-th constituent plane $P^{(d)}$ of a color picture P with width W and height H is defined as follows:

$$P^{(d)} = \{p^{(d)}_{i,j} \mid 0 \le i \le W-1, 0 \le j \le H-1\}.$$

A unit block of watermarking is an $L \times L$ pixel block in which the values of all the pixels are changed in the same direction (i.e., all of them are either increased or decreased). L is called the block size.

A pseudo-random noise (PN) sequence R is a pseudrandom sequence of integers $+1$ and -1:

$$R \;=\; \{r_{k,l} \mid r_{k,l} \in \{-1,+1\}, 0 \le k \le \lfloor W/L \rfloor - 1,$$

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$$0 \le l \le \lfloor H/L \rfloor - 1\}.$$

A mask M using a PN sequence R is defined as

$$\begin{aligned} M &= \{m_{i,j} \mid m_{i,j} = r_{\lfloor i/L \rfloor, \lfloor j/L \rfloor}, 0 \le i \le W-1, \\ &\quad 0 \le j \le H-1\}. \end{aligned}$$

The mask is the watermark pattern actually embedded into the constituent plane.

2.2 Basic procedures

For clarity, we here describe the method for one-bit watermarking. In a multi-bit case, each bit is assigned for each area of the picture and is embedded and detected by the same principle as in the one-bit case. The embedding part of the one-bit watermarking method is as follows:

Step E1. Resolve P into constituent planes, of which the two planes $P^{(0)}$ and $P^{(1)}$ are used for watermarking.

Step E2. Make the mask M from R and L referring to the width and height of P.

Step E3. Embed the PN sequence R (i.e., the corresponding mask M) into $P^{(0)}$ by the operation

$$p'^{(0)}_{i,j} = p^{(0)}_{i,j} + \alpha^{(0)}_{i,j} m_{i,j},$$

where $\alpha^{(d)}_{i,j} (> 0)$ represents watermark strength at $p^{(d)}_{i,j}$. This operation increases or decreases $p^{(0)}_{i,j}$ by the degree $\alpha^{(0)}_{i,j}$ depending on the value of $m_{i,j}$.

Step E4. Embed R into $P^{(1)}$ by the operation

$$p'^{(1)}_{i,j} = \begin{cases} p^{(1)}_{i,j} + \alpha^{(1)}_{i,j} m_{i,j} & \text{if } b = 1 \\ p^{(1)}_{i,j} - \alpha^{(1)}_{i,j} m_{i,j} & \text{if } b = 0. \end{cases}$$

According to the value of bit b, this operation embeds into $P^{(1)}$ a pattern that is either the same as or the reverse of that embedded into $P^{(0)}$.

Step E5. Construct P' from $P'^{(0)}$ and $P'^{(1)}$.

The detection part of the one-bit watermarking method is as follows:

Step D1. Extract the two constituent planes $P'^{(0)}$ and $P'^{(1)}$ by the same way as in embedding.

Step D2. Calculate the covariance value c by the operation

$$c = \langle (p'^{(0)}_{i,j} - \langle p'^{(0)}_{i,j} \rangle)(p'^{(1)}_{i,j} - \langle p'^{(1)}_{i,j} \rangle) \rangle, \qquad (1)$$

where $\langle \bullet \rangle$ means the average value over i and j.

Step D3. If $c > 0$, then detect $b = 1$; if $c < 0$, then detect $b = 0$; if $c = 0$, b is not detected.

The detection of the embedded bit can be based on the correlation between the two planes. Even after random geometric distortion, the PN sequences embedded in $P'^{(0)}$ and $P'^{(1)}$ are still synchronized, because these two planes are distorted in the same way. The embedded bit can therefore still be detected.

3 Dealing with random geometric distortion

3.1 Theoretical analysis of basic procedure

As mentioned in Section 2.2, the determination of the bit value is based on the covariance value c (formula (1) of Step D2), which by the definition of $P'^{(0)}$ and $P'^{(1)}$ can be transformed as follows:

$$\begin{aligned} c &= \langle (p^{(0)}_{i,j} - \langle p^{(0)}_{i,j} \rangle)(p^{(1)}_{i,j} - \langle p^{(1)}_{i,j} \rangle) \rangle && (2) \\ &+ (\langle p^{(1)}_{i,j} \alpha^{(0)}_{i,j} m_{i,j} \rangle - \langle p^{(1)}_{i,j} \rangle \langle \alpha^{(0)}_{i,j} m_{i,j} \rangle) && (3) \\ &\pm (\langle p^{(0)}_{i,j} \alpha^{(1)}_{i,j} m_{i,j} \rangle - \langle p^{(0)}_{i,j} \rangle \langle \alpha^{(1)}_{i,j} m_{i,j} \rangle) && (4) \\ &\pm (\langle \alpha^{(0)}_{i,j} \alpha^{(1)}_{i,j} \rangle - \langle \alpha^{(0)}_{i,j} m_{i,j} \rangle \langle \alpha^{(1)}_{i,j} m_{i,j} \rangle), \end{aligned}$$

where "±" means "+" when the embedded bit b is 1 and "−" when b is 0. The term (2) represents covariance between $P^{(0)}$ and $P^{(1)}$, and depends only on the nature of the picture and the selection of the two constituent planes. The former parts of the terms (3) and (4), $\langle p^{(1)}_{i,j} \alpha^{(0)}_{i,j} m_{i,j} \rangle$ and $\langle p^{(0)}_{i,j} \alpha^{(1)}_{i,j} m_{i,j} \rangle$, have expectation of 0, as shown in the analysis of the Patchwork watermarking method [6]. The latter parts of the terms (3) and (4) also have expectations of 0. The expectation and the variance of c for $L = 1$ can thus be evaluated as follows:

$$E(c) = \langle \hat{p}^{(0)}_{i,j} \hat{p}^{(1)}_{i,j} \rangle \pm \langle \alpha^{(0)}_{i,j} \alpha^{(1)}_{i,j} \rangle \left(1 - \frac{1}{HW}\right),$$

$$\begin{aligned} V(c) = &\frac{1}{HW} \left\{ \langle \alpha^{(1)2}_{i,j} \hat{p}^{(0)2}_{i,j} \rangle + \langle \alpha^{(0)2}_{i,j} \hat{p}^{(1)2}_{i,j} \rangle \pm 2 \langle \alpha^{(0)}_{i,j} \alpha^{(1)}_{i,j} \hat{p}^{(0)}_{i,j} \hat{p}^{(1)}_{i,j} \rangle \right\} \\ &+ \frac{1}{H^2 W^2} \left\{ \left(2 + \frac{1}{HW}\right) \langle \alpha^{(0)2}_{i,j} \alpha^{(1)2}_{i,j} \rangle + \langle \alpha^{(0)2}_{i,j} \rangle \langle \alpha^{(1)2}_{i,j} \rangle \right. \\ &- \left. \langle \alpha^{(0)}_{i,j} \alpha^{(1)}_{i,j} \rangle^2 \right\}, \end{aligned}$$

where $\hat{p}^{(d)}_{i,j}$ is given by $\hat{p}^{(d)}_{i,j} = p^{(d)}_{i,j} - \langle p^{(d)}_{i,j} \rangle$. From the above formula, the requirements for reliable detection after random geometric distortion are that the noise, especially the variances, $\langle \alpha^{(1)2}_{i,j} \hat{p}^{(0)2}_{i,j} \rangle$ and $\langle \alpha^{(0)2}_{i,j} \hat{p}^{(1)2}_{i,j} \rangle$, and the covariances, $\langle \hat{p}^{(0)}_{i,j} \hat{p}^{(1)}_{i,j} \rangle$ and $\langle \alpha^{(0)}_{i,j} \alpha^{(1)}_{i,j} \hat{p}^{(0)}_{i,j} \hat{p}^{(1)}_{i,j} \rangle$, should be reduced. The next section thus concentrates on the noise reduction.

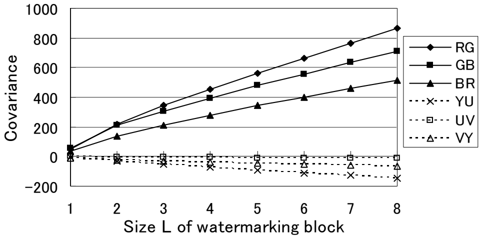


Figure 1: Covariances between two constituent planes of the standard picture Lenna.

3.2 Improvement of basic procedure

3.2.1 Noise-reduction preprocess

Before Step D2 of the detection procedure, the plane $P^{(d)}$ $(d = 0, 1)$ is processed according to the following equation:

$$\begin{aligned} p'^{(d)}_{i,j} &= p'^{(d)}_{i,j} \\ &- (p'^{(d)}_{i-L,j} + p'^{(d)}_{i,j-L} + p'^{(d)}_{i+L,j} + p'^{(d)}_{i,j+L})/4. \end{aligned}$$

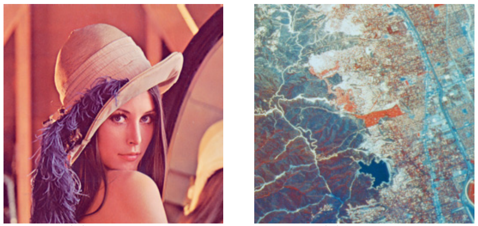
Because pixels neighboring in the horizontal and vertical directions tend to have similar values, this preprocess reduces the variance of the plane $P^{(d)}$ when L is small.

3.2.2 Selection of two planes

The two planes for watermarking should be selected in such a way that the covariance between these planes before watermarking is small. Because RGB and YUV color systems are generally used on computers, we select the planes from them. Fig. 1 shows covariances between two planes in a standard picture Lenna after the noise reduction preprocess. The size L of watermarking block in Fig. 1 corresponds to the pixel distance between the target pixel and the surrounding pixels. The covariances between U and V are the smallest absolute values. The U and V planes are therefore selected for watermarking.

3.2.3 Shift of plane

Two constituent planes of the same picture have an inherent correlation. We therefore reduce this inherent correlation by shifting one of the two planes in the watermark detection, that is, watermarks are embedded in $P^{(1)}$ at the position shifted by $\mathrm{s} = (\Delta x, \Delta y)$. We call s a shift vector. Corresponding to the shifted embedding, shifted watermark detection is done by correlating $P^{(0)}$ with $P^{(1)}$ shifted by $-\mathrm{s}$. This shifted detection desynchronizes while keeping the PN sequences embedded in the two planes synchronized. Thus Step E4 of the embedding procedure and the Step D2 of the detection procedure are changed as follows:



(a) Lenna. (b) Aerial.

(c) Pepper. (d) Girl.

Figure 2: Standard pictures for evaluation.

Step E4'. Embed R into $P^{(1)}$ by the operation

$$p'^{(1)}_{i,j} = \begin{cases} p^{(1)}_{i,j} + \alpha^{(1)}_{i,j} m_{i-\Delta x, j-\Delta y} & \text{if } b = 1 \\ p^{(1)}_{i,j} - \alpha^{(1)}_{i,j} m_{i-\Delta x, j-\Delta y} & \text{if } b = 0, \end{cases}$$

where i and j satisfy $\Delta x \le i \le W - 1$ and $\Delta y \le j \le H - 1$ respectively.

Step D2'. Calculate the covariance value c as

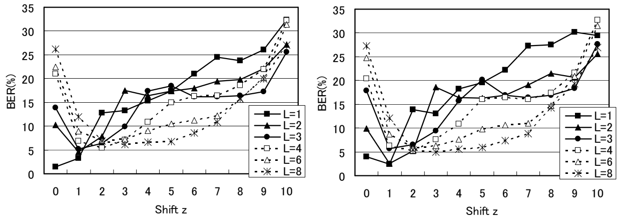
$$c = \langle (p'^{(0)}_{i,j} - \langle p'^{(0)}_{i,j} \rangle)(p'^{(1)}_{i+\Delta x, j+\Delta y} - \langle p'^{(1)}_{i+\Delta x, j+\Delta y} \rangle \rangle.$$

4 Experimental evaluation

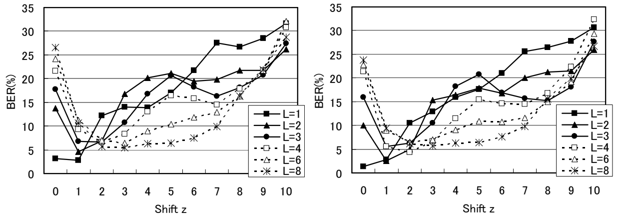
The ability of watermarks to survive random geometric distortion was evaluated experimentally by using the 256 × 256-pixel standard pictures shown in Fig. 2.

4.1 Watermark strength and picture quality

Watermark strength $\alpha^{(d)}_{i,j}$ should be controlled for each pixel $p^{(d)}_{i,j}$ in each of chrominance planes U and V to minimize the degradation of picture quality. Since little method for controlling the watermark strength in the planes U and V has been proposed, we instead applied the method based on the human visual model of the luminance plane [7, 8] to determine $\alpha^{(d)}_{i,j}$. The PSNR values in the four evaluated pictures were 34 dB through 37 dB. These PSNR values are slightly smaller than those used for watermarking in the luminance plane because color watermarks are less perceptible to human eyes than luminance watermarks [9].



(a) Lenna (b) Aerial



(c) Pepper (d) Girl

Figure 3: Bit error rates. Shift z means the shift vector $\mathbf{s} = (z, z)$.

4.2 Survivability

We used StirMark 3.1 with default parameters as the representative random geometric distortion by using the following evaluation parameters: (1) the number of bits embedded in each picture (N) is 256, (2) several block sizes ($L = 1, 2, 3, 4, 6,$ and 8) were used, and (3) oblique shift vectors of different sizes, i.e., $\mathbf{s} = (1,1), (2,2), \ldots, (10,10)$ as well as the unshifted case $\mathbf{s} = (0,0)$ are employed for the evaluation. [1]

Fig. 3 shows the bit error rate (BER) for each combination of L and $\mathbf{s}$ in the detection from the four evaluated pictures. Each point in these graphs means the number of erroneously detected bits divided by 256000 bits (i.e., 256 bits × 1000 different StirMark distortions).

From the data plotted in these figures, we can infer that the plane shift is effective. That is, the BER is high at $\mathbf{s} = (0,0)$ and initially decreases with increasing $\mathbf{s}$. The BER, however, increases again at roughly $\mathbf{s} = (2,2)$ or $(3,3)$. It is thus most effective at $\mathbf{s} = (1,1)$ and $(2,2)$. For all the evaluated pictures, we can see that the BER is less than 5% at $L = 1$ and 2 and the effective values of $\mathbf{s}$ and is less than 7% at $L = 3$, 4, 6, and 8 and the same values of $\mathbf{s}$. If we use error correction codes for 18-bit data (e.g., $(255, 131)$ BCH code), we have 131 bits for net information. The proposed method can detect over 100 bits embedded in 256 × 256-pixel pictures after random geometric distortion without using searches or special patterns.

5 Conclusion

This paper presented a watermarking method for color still pictures immune to random geometric distortion. The watermark patterns are embedded in two of the three planes constituting a color picture so that these two planes have a specific correlation. The detection of the embedded information is then based on the correlation value between these two constituent planes. Because the two planes of the picture are distorted in the same way, their correlation is not affected by random geometric distortion and the detection is therefore immune to the distortion. Experimental evaluations using StirMark confirmed that over 100 bits embedded in 256×256-pixel pictures can be correctly detected without using searches or special patterns.

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[1] It is known as a rule of thumb that a picture has less self-correlation in oblique directions. This rule implies that shift vectors in oblique directions are effective in reducing the correlation between two constituent planes. We therefore tried oblique shift vectors for this evaluation.