Applied Mathematics & Information Sciences
An International Journal

http://dx.doi.org/10.12785/amis/090307

On the Security of Robust Image Watermarking Algorithm based on Discrete Wavelet Transform, Discrete Cosine Transform and Singular Value Decomposition

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Received: 8 Jul. 2014, Revised: 9 Oct. 2014, Accepted: 10 Oct. 2014
Published online: 1 May 2015

Abstract: Among emergent applications of digital watermarking, owner identification, proof of ownership and transaction tracking are applications that protect data by embedding the owner's information (watermark) in it. Recently, a robust image watermarking scheme based on discrete wavelet transform, discrete cosine transform and singular value decomposition was proposed by Hu et al. [1]. However, this scheme has shown some drawbacks. In this paper, we present two ambiguity attacks that clearly demonstrate the ineffectiveness of the above scheme some watermarking applications, such as proof of ownership, transaction tracking and data authentication.

Keywords: Ambiguity attack, image watermarking, discrete wavelet transform, discrete cosine transform, singular value decomposition.

1 Introduction

One of the most important advantages of the numeric era is the widespread use of Internet and computers, which is the result of exchanging digital media. However, illegal reproduction of data has also emerged with this extraordinary revolution and is raising questions and concerns about ownership rights. As a solution to this issue, we found Digital watermarking which consists in embedding digital data into digital contents in order to guarantee the ownership and the integrity. The basic requirements for a secure watermarking scheme are imperceptibility, robustness, capacity and security.

Digital image watermarking algorithms proposed in literature are mainly grouped into two classes: spatial [2, 3] and transform domains [4,5]. In the literature, watermarking algorithms based on singular value decomposition (SVD) have been proposed [6,7,8]. There are several advantages of using SVD in digital watermarking algorithm such as: First, the size of the matrices obtained from SVD transformation is not fixed, they can be square or rectangle matrices. Second, singular values in a digital image exhibit a very good stability, that is, when a small perturbation is added to an image, its singular values do not change significantly. Third, each singular value specifies the luminance of the image while the corresponding pair of left and right singular matrices specifies the geometry of the image [9]. However, beside the above advantages, some SVD-based watermarking algorithms [6,10,11,12,13] are vulnerable to attacks and do exhibit prohibitively high probabilities of false positive detections as reported in recent literature by Loukhaoukha [14,15], Rykaczewski [16], Zhang and Li [17], Zhang et al. [18], Loukhaoukha and Chouinard [19] and Xiao et al. [20].

This paper studies the robust image watermarking based on discrete wavelet transform, discrete cosine transform and singular value decomposition proposed by

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Hu et al. [1]. We show that this algorithm does not bind an original image to a watermark and cannot be used in some security applications such as owner identification, proof of ownership, and transaction tracking. The rest of this paper is organized as follows. In the section 2, we briefly review the concept of singular value decomposition. The watermarking algorithm proposed by Hu et al. [1] is described in section 3. In section 4, we present two ambiguity attacks on this watermarking algorithm. Experimental results on these attacks are presented in section 5. Conclude are drawn in section 6.

2 Singular value decomposition

Although any given matrix of size $M \times N$ can be decomposed using the singular value decomposition (SVD), our discussion will be limited to square matrices only. The singular value decomposition of an image I of size $N \times N$ is defined as follow:

$$I = U \cdot S \cdot V^T \tag{1}$$

where $U \in \Re^{N\times N}$ and $V \in \Re^{N\times N}$ are orthogonal matrices called matrices of left and right singular vectors. $S \in \Re^{N\times N}$ is a diagonal matrix containing nonnegative terms and also known as singular value matrix. A simple example of the SVD operation is given below :

$$A = \begin{bmatrix} 151 & 140 & 131 \\ 74 & 70 & 72 \\ 135 & 144 & 154 \end{bmatrix} = \begin{bmatrix} -0.6573 & 0.6990 & 0.2816 \\ -0.3365 & 0.0622 & -0.9396 \\ -0.6743 & -0.7124 & 0.1943 \end{bmatrix} \times \begin{bmatrix} 370.6924 & 0 & 0 \\ 0 & 19.5494 & 0 \\ 0 & 0 & 1.9929 \end{bmatrix} \times$$

$$\begin{bmatrix} -0.5805 & 0.7148 & -0.3900 \\ -0.5737 & -0.0192 & 0.8188 \\ -0.5778 & -0.6991 & -0.4213 \end{bmatrix}^T$$

There is several proprieties of the SVD such as :

–Singular values correspond to the luminance of the image. Suppose that the image represented in figure 1a is decomposed using SVD, then its singular values are first multiplied by 2, and in a second time divided by 2. The obtained images are illustrated in figures 1b and 1c, respectively. It is clear that the luminance of the images changed when their singular values change.

–The singular vectors specify the intrinsic geometry properties of the image. The singular vectors of the same image represented in figure 1a are slightly modified. Firstly, a values of 0.04 is added to matrix U, and secondly the same values is subtracted from matrix V. The obtained image is represented in figure 2, where one can see that the geometry of image is modified significantly.

–Singular values have a good stability, which means that a slight variation of the singular values do not affect the visual perception of the image. Figure 3 shows an example of the stability of the singular values, where a small perturbation, of value equal to 5, is added in the singular values. One can see that this perturbation do not affect the visual perception of the reconstructed image and the Peak-Signal-to-Noise Ratio (PSNR) between original image and reconstructed image is equal to 52.20 dB

(a) Original image

(b) Reconstructed image: SVs multiplied by 2

(c) Reconstructed image: SVs divided by 2

Fig. 1: Impact of changing singular values.

3 Image watermarking scheme based on DWT, DCT and SVD

In this section, we briefly review the watermarking algorithm based on discrete wavelet transform, discrete cosine transform and singular value decomposition

(a) Original image

(b) Reconstructed image

Fig. 2: Impact of changing singular vectors.

(a) Original image

(b) Reconstructed image

Fig. 3: Impact of slight variation of singular values.

proposed by Hu et al. [1]. The watermark embedding process comprises the following steps:

1. Transform the original image I from RGB color space to YC_bC_r color space to obtain I_Y, I_{Cb} and I_{Cr} images, using equation 2.

$$\begin{cases} Y &= 0.257 \cdot R + 0.504 \cdot G + 0.098 \cdot B + 16 \\ C_b &= -0.148 \cdot R - 0.291 \cdot G + 0.439 \cdot B + 128 \\ C_r &= 0.439 \cdot R - 0.368 \cdot G - 0.071 \cdot B + 128 \end{cases} \tag{2}$$

2. Apply the one-level discrete wavelet transform (DWT) to gray-level image I_Y to obtain four sub-band images $I_{Y,LL}$, $I_{Y,LH}$, $I_{Y,HL}$ and $I_{Y,HH}$.
3. Apply the discrete cosine transform (DCT) to the LL sub-band image $I_{Y,LL}$ to obtain frequency components D_Y.
4. Apply singular value decomposition (SVD) to frequency components D_Y to obtain matrix S_1.

$$D_Y = U_1 \cdot S_1 \cdot V_1^T \tag{3}$$

5. Modify the singular values of S_1 with the watermark image to obtain matrix S_0 as defined by equation 4, where α is the scale factor ($0 < \alpha < 1$) that controls the strength of the watermark to be inserted.

$$S^{'} = S_1 + \alpha \cdot W \tag{4}$$

6. Apply SVD to matrix $S^{'}$ to obtain matrix S_2.

$$S^{'} = U_2 \cdot S_2 \cdot V_2^T \tag{5}$$

7. Obtain watermarked image $D_Y^{'}$ by multiplying matrices U_1, S_2 and V_1^T.

$$D_Y^{'} = U_1 \cdot S_2 \cdot V_1^T \tag{6}$$

8. Apply the inverse DCT to image $D_Y^{'}$ to obtain image $I_{Y,LL}^{'}$.
9. Apply the inverse DWT to images $I_{Y,LL}$, $I_{Y,LH}$, $I_{Y,HL}$ and $I_{Y,HH}$ to obtain image $I_Y^{'}$.
10. Use equation 7 on image $I_Y^{'}$ with I_{Cb} and I_{Cr} to transform the YC_bC_r color space into the RGB color space, and then produce color watermarked image I_W.

$$\begin{cases} R &= 1.164 \cdot (Y - 16) + 1.596 \cdot (C_r - 128) \\ G &= 1.164 \cdot (Y - 16) - 0.391 \cdot (C_b - 128) - 0.813 \cdot (C_r - 128) \\ B &= 1.164 \cdot (Y - 16) + 2.018 \cdot (C_b - 128) \end{cases} \tag{7}$$

Note that, S_1, U_2 and V_2 will be kept to be used in the watermark extracting process, which is achieved by the following steps:

1. Transform the watermarked image I_W from the RGB color space to the YC_bC_r color space, and then obtain gray-level image I_{YW}.
2. Apply the one-level DWT to image I_{YW} to obtain four sub-band images $I_{YW,LL}$, $I_{YW,LH}$, $I_{YW,HL}$ and $I_{YW,HH}$.

3.Apply the DCT to image $I_{YW,LL}$ to obtain frequency components D_{YW}.
4.Apply the SVD to frequency components D_{YW} to obtain matrix S_{W1}.

$$D_{YW} = U_{W1} \cdot S_{W1} \cdot V_{W1}^T \tag{8}$$

5.Calculate the difference between S_{W1} and S_2 to modify S'_{W1}, where $0 < \beta < 1$ and S_{th} is the given threshold.

$$S'_{W1} = \begin{cases} (1-\beta) \cdot S_{W1} + \beta \cdot S_2 & \text{if } |S_{W1} - S_2| \geq S_{th} \\ \beta \cdot S_{W1} + (1-\beta) \cdot S_2 & \text{otherwise} \end{cases} \tag{9}$$

6.Obtain S''_W by multiplying matrices U_2, S'_{W1} and V_2^T.

$$S''_W = U_2 \cdot S'_{W1} \cdot V_2^T \tag{10}$$

7.Obtain the extract watermark image using the following equation:

$$\hat{W} = \frac{S''_W - S_1}{\alpha} \tag{11}$$

4 Ambiguity attacks

The basis of the ambiguity attack has first been introduced by Craver et al. [21]. As a consequence of this attack, both the owner and an attacker are able to correctly extract their watermarks from the watermarked image, but neither can prove his ownership of the image, thus, this situation leads to confusion. In this section, we describe two ambiguity attacks on the image watermarking algorithm based on discrete wavelet transform, discrete cosine transform and singular value decomposition proposed by Hu et al. [1], which show that this algorithm cannot be used for owner identification, proof of ownership, and transaction tracking.

4.1 First attack

Suppose that Alice, which is the legitimate owner, has performed the embedding steps (from 1 to 10) to embed her own watermark W_O into the original image I to get watermarked image denoted by I_{W_O}. To claim the ownership of the image I, Alice performs the extracting steps (from 1 to 7). If her watermark is successfully extracted from the watermarked image I_{W_O}, she is considered as the rightful owner. However, if we suppose that Bob, which considered as an attacker, has done the step 6 of embedding process on his fake watermark, W_F, to get the singular vectors U_{W_F} and V_{W_F}. In order to prove his ownership of the original image I, he performs the extracting steps as follows:

1.Perform steps from 1 and 5 to obtain S'_{W1}.
2.By supplying U_{W_F}, V_{W_F}, step 6 can be achieved using the following equation :

$$S''_{W_F} = V_{W_F} \cdot S'_{W1} \cdot V_{W_F}^T \tag{12}$$

3.3) The extracted watermark image is obtained using the following equation:

$$\hat{W}_F = \frac{S''_{W_F} - S_1}{\alpha} \tag{13}$$

Thus, a fake watermark $\hat{W}_F$, which is Bob's watermark, is successfully extracted from watermarked image I_{W_O}, which is not supposed to contain it. The block diagram of this attack is represented in figure 4.

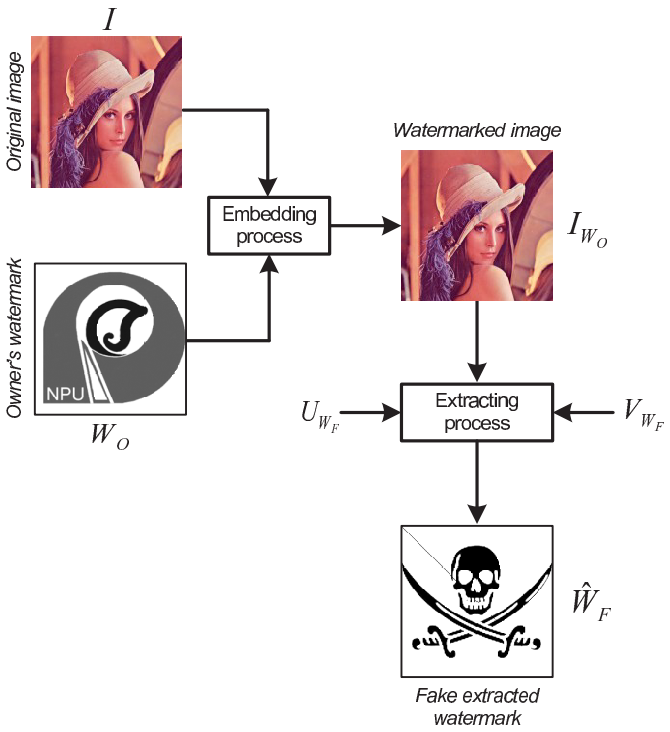


Fig. 4: Block diagram of the first attack.

4.2 Second attack

Consider the scenario where Alice is the owner of the image I which is watermarked by her own watermark W_O to obtain the watermarked image I_{W_O}. The attacker Bob can directly obtain I_{W_O} and performs the embedding steps from 1 to 10 to embed his watermark W_F, into the watermarked image I_{W_O} to obtain finally the watermarked image $I_{W_{OF}}$. If Alice wishes to claim ownership of the original image I, she needs to perform extracting steps

from 1 to 7 to get the extracted watermark W_O from the watermarked image I_{W_O}. In the other hand, Bob can claim the ownership of image I by performing the extracting steps from 1 to 7 to his own watermark W_F by claiming $I_{W_{OF}}$ to be original watermarked image instead of I_{W_O}. This situation creates ambiguity about who is the legitimate owner of the original image I. Finally, no one knows who is telling the truth Alice or Bob. The block diagram of this attack is represented in figure 5.

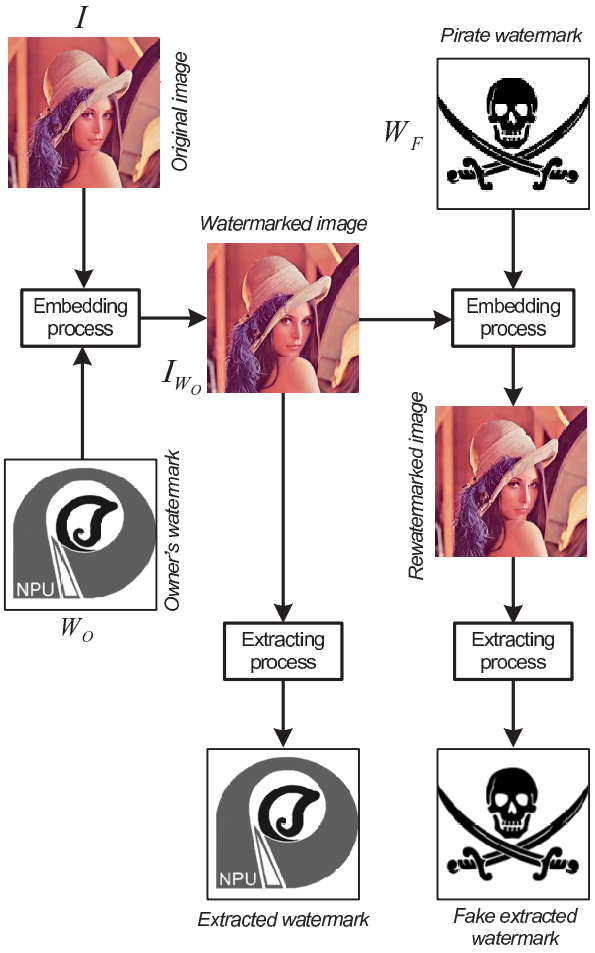


Fig. 5: Block diagram of the second attack.

5 Experimental results

In this section, experiments were carried out to prove the feasibility of proposed attacks described in section 4. Color original images Lena and Baboon of size 512×512, and owner and attacker watermarks of size 256×256, illustrated in figure 6, were used in the experiments.

(a) Lena **(b)** Baboon

(c) Owner watermark **(d)** Attacker watermark

Fig. 6: Original and watermark images.

In the attacks scenarios, we played the role of Bob (the attacker) and for each attack, two experiments are performed. First, Alice who protects her own images Lena, denoted by I^1, and Baboon, denoted by I^2, by embedding her own watermark W_O using the embedding process described in section 3 to obtain then the watermarked images $I^1_{W_O}$ and $I^2_{W_O}$, respectively.

5.1 First attack

In order to extract the embedded watermark from the watermarked images $I^1_{W_O}$ and $I^2_{W_O}$, the extracting process described in section 3 is performed. If the singular vectors U_{W_F} and V_{W_F} obtained from the attacker watermark W_F, are used instead of U_W and V_W obtained from the owner watermark W_O. The extracted watermarks $\hat{W}_1$ and $\hat{W}_2$ from watermarked images $I^1_{W_O}$ and $I^2_{W_O}$ respectively, are fake watermarks, which are visually and geometrically similar to the attacker watermark. The normalized correlation values (NC) between extracted watermarks, $\hat{W}_1$ and $\hat{W}_2$, and attacker watermark W_F are 0.9715 and 0.9714, respectively. The embedded and extracted watermarks of these experiments are illustrated in figures 7 and 8. One can see that the extracted watermarks are visually and geometrically similar to the attacker watermark although the embedded one in original images is the owner watermark.

(a) Embedded watermark **(b)** Extracted watermark

Fig. 7: First experiment.

(a) Embedded watermark **(b)** Extracted watermark

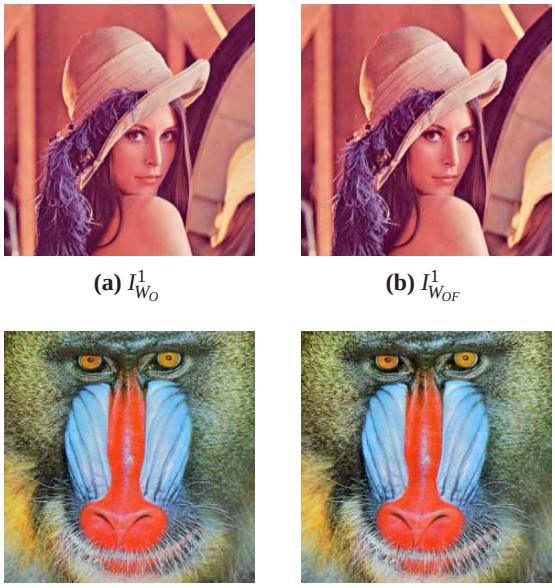
Fig. 8: Second experiment.

5.2 Second attack

Using the watermark embedding process described in section 3, the attacker watermark W_F is embedded in the watermarked images $I^1_{W_O}$ and $I^2_{W_O}$, to obtain the watermarked images $I^1_{W_{OF}}$ and $I^2_{W_{OF}}$, which have PSNR values with their corresponding original images equal to 44.05 dB and 41.90 dB, respectively. The watermarked images are presented in figure 9b and 9d.

According to the scenario presented in section 4.2, Alice obtains the extracted watermarks W^1_O and W^2_O from the watermarked images $I^1_{W_O}$ and $I^2_{W_O}$ which are presented in figures 9a and 9c, respectively. The extracted watermarks are presented in figures 10a and 10c, where it is clear that they are visually and geometrically similar to the owner watermark W_O. The normalized correlation (NC) values between the owner watermark W_O and the extracted watermarks W^1_O and W^2_O are equal to 0.999 and 0.999, respectively.

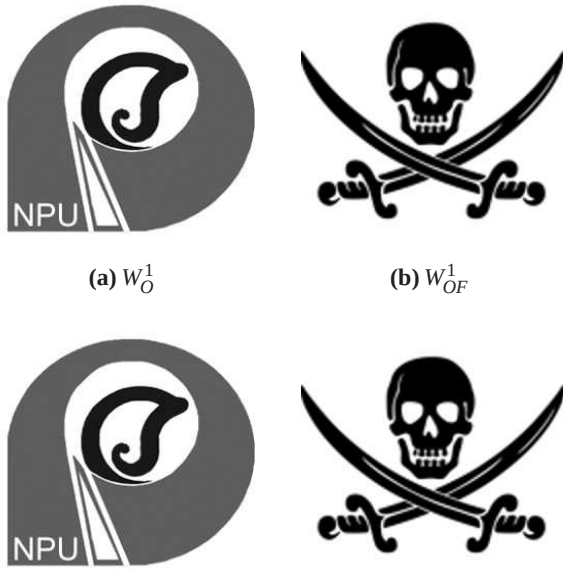
In the other hand, we can also extract the watermarks W^1_{OF} and W^2_{OF} from the watermarked images $I^1_{W_{OF}}$ and $I^2_{W_{OF}}$, respectively. These extracted watermarks are presented in figures 10b and 10d, where it is clear that they are visually and geometrically similar to the attacker watermark W_F. The normalized correlation (NC) obtained between the attacker watermark W_F and the extracted watermarks W^1_{OF} and W^2_{OF} are 0.999 and 0.999, respectively.



(a) $I^1_{W_O}$ **(b)** $I^1_{W_{OF}}$

(c) $I^2_{W_O}$ **(d)** $I^2_{W_{OF}}$

Fig. 9: Watermarked images.



(a) W^1_O **(b)** W^1_{OF}

(c) W^2_O **(d)** W^2_{OF}

Fig. 10: Extracted watermarks from watermarked images illustrated in figure 9.

According to the above results, the extracted watermarks make an ambiguity situation about who is the owner of original image I because no one knows which is telling the truth Alice or Bob. Consequently and as mentioned above, the image watermarking algorithm based on discrete wavelet transform, discrete cosine transform and singular value decomposition should not be used for owner identification, proof of ownership, and transaction tracking.

6 Conclusion

In this paper, we have demonstrated that the image watermarking algorithm based on discrete wavelet transform, discrete cosine transform and singular value decomposition proposed by Hu et al. [1] fails to resist two ambiguity attacks. In the first one, using the singular vectors of any fake watermark in the extracting process, the attacker can always claim that this watermark is the embedded one, hence, proves his ownership of the watermarked image. In the second attack, any watermarked image is publicly available which can be re-watermarked by an attacker's watermark. Later, this attacker one can claim that the embedded watermark is his one. Experimental results prove that this algorithm should not be used for proof of ownership, transaction tracking and data authentication.

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