Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 8 Issue 5, May - 2021

Multi-channel Based Zero-Watermarking Algorithm for Color Image Against Cropping Attack

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***Abstract*—In order to enhance the capability of the existing watermarking algorithms against various attacks (e.g., cropping, smearing, row and column removal) with information loss, a digital zero-watermarking algorithm based on Non-negative Matrix Factorization (NMF) and Histogram Invariant Moments (HIMs) is proposed to resist large-scale cropping and smearing attacks. First, the single- channel contained in the original color image (i.e., R, G, and B channels) is regarded as the grayscale image matrix, and then the grayscale image matrix V of each single-channel is decomposed by non- negative matrix to obtain the base matrix W and coefficient matrix H. Since NMF's partial perception of global characteristics, we can use the partial V matrix information and the corresponding coefficient matrix H to reconstruct the W matrix. Finally, the V matrix can be recovered by using W matrix and H matrix. In addition, In the watermark registration and extraction algorithm, the modified version of HIMs is used to design and construct zero watermark information. The experimental results show that, when the area of cropping or smearing reaches 80%, the watermark can still be correctly detected, and the algorithm is also robust against noise, filtering, JPEG compression and geometric attacks.**

Keywords −Non-negative matrix factorization; Zero-watermarking; Robustness; Histogram invariant moments

I. INTRODUCTION

Robust digital watermarking algorithm against geometric attacks is a hot topic in the field of multimedia information security [1, 2]. The existing watermarking algorithms against geometric attacks are effective for traditional geometric transformation (e.g., rotation, scaling, translation, and affine transformation) and conventional image processing, such as noise addition, lossy compression, and filtering, etc. However, there are few reports on large-scale cropping attack with information loss at home and abroad. Among those robust watermarking algorithms, the watermark detector can extract watermark information to a certain extent for weak cropping (information loss is less than 25%). However, in the face of a large-scale cropping of information loss (strong cropping attack), the watermark detector can not correctly extract the watermark information, thus, the algorithm is invalid. Xiang et al. [3] proposed a watermarking algorithm based on low-frequency statistical features of an image, they embed the watermark into the low-frequency histogram and mean statistical features of the image. The experimental results show that the algorithm can resist the cropping attack well, however, the embedded watermark capacity is smaller. Du et al. [4] proposed an image watermarking algorithm based on histogram adjustment to resist geometric attacks. Compared with the proposed algorithm in ref [3], this algorithm can improve the embedding capacity of the watermark information obviously and is also robust to cropping attacks. However, the robustness of the algorithm is at the expense of the invisibility of the watermark, so this algorithm remain has some limitations. The anti-geometric attack algorithms based on moment invariants proposed in refs [5, 6] has good robustness against rotation, scaling and translation attacks, but it can not effectively resist strong cropping attacks. This is mainly because most moment invariants are based on the global features of an image and can not do anything for local cropping operation. Lin et al. [7]

proposed an anti-shearing attack watermarking method based on equal modulation. The algorithm embeds the watermark into the low-frequency coefficients of the image after wavelet decomposition through equal modulation. However, with the image being sheared, the watermark information is irrecoverably lost. The greater the degree of shearing, the more serious the watermark loss. All the algorithms mentioned above need to solve a common problem: the contradiction between invisibility and robustness. Zero-watermarking technology can solve this problem well, it does not need to modify any information of the original image, mainly uses the important features of the image to construct watermark information, so that its robustness and security are enhanced. Wen et al. [8] proposed the concept of zero watermark for the first time. In this paper, high-order cumulants are used to extract image features to construct zero watermark. Experiments show that this method has good performance. In recent years, zero-watermarking technology has been rapidly promoted after it was proposed by Wen, and the scientific research achievements and reports in this field are increasing rapidly [9-11]. Since Lee et al. [12] first proposed NMF algorithm in nature, NMF has been continuously improved and developed. At present, the NMF has been successfully applied in many fields, such as face recognition, image fusion, image retrieval, text clustering, and blind source separation and so on [13, 14], but few in the field of digital watermarking. Based on the property that NMF can perceive the whole by part, a novel zero-watermarking algorithm is proposed to resist strong cropping and smearing attacks combined with histogram invariant moments.

II. DEFINITION AND CALCULATION OF NMF

Suppose that a digital image matrix $V_{n\times m}$ can be decomposed into the product of two non-negative matrices $W_{n\times r}$ and $H_{r\times m}$:

$$V_{n\times m} \approx W_{n\times r} H_{r\times m} = \sum_{i=1}^{r} W_{n\times i} H_{i\times m} \tag{1}$$

Here, W is base matrix, H is coefficient matrix, and r is the dimension of base matrix.

The objective function of NMF is generally expressed as:

$$F(W,H) = \sum_{i=1}^{m}\sum_{j=1}^{n}[V_{ij} - (W_{ij}H_{ij})]^2 \tag{2}$$

Where $W_{ij} \ge 0, H_{ij} \ge 0, i = 1,2\dots m. j = 1,2\dots n.$ M and N are the number of rows and columns of the original matrix V, respectively. Eq. (1) can be regarded as adding Possion noise or Gauss noise to $W_{ij}H_{ij}$ to produce V_{ij}, namely, $V = WH + E$, E represents noise. If the Possion noise is taken as E, the following iterative algorithm can be obtained:

$$\begin{cases} W_{ia} \leftarrow W_{ia} \sum \dfrac{V_i}{(WH)_i} H_a \\ W_{ia} \leftarrow \dfrac{W_{ia}}{\sum_j W_{ja}} \\ H_a \leftarrow H_a \sum W_{ia} \dfrac{V}{(WH)_i} \end{cases} \tag{3}$$

$$\forall i,a,b,j \text{ 则有 } \begin{cases} W_{ia} \ge 0 \\ W_{bj} \ge 0 \end{cases} \tag{4}$$

Where j is the column of the matrix and i is the row of the matrix. After several iterations, $V \approx WH$.

III. HISTOGRAM INVARIANT MOMENTS

The histogram of an image reflects the statistical characteristics of the image. It expresses the proportion of the area or the number of pixels with different gray value in the whole image. The amount of information contained in an image can also be calculated through the histogram. Therefore, when the imaging conditions of the same region change, although the image changes a lot in the sense, the corresponding histogram will not change much in the shape, so the information contained in the histogram can be used to define the image features. In order to make use of the information of histogram, in this paper, we define several invariant moments of image histogram which are independent of translation, rotation and scaling change.

Generally, according to the multi-channel methodology [15, 16], the RGB representation of the color image, $f_c(x,y)$ is represented as:

$$f_c(x,y) = (f_R(x,y), f_G(x,y), f_B(x,y)) \tag{5}$$

The three color channels are $f_R(x,y)$, $f_G(x,y)$, and $f_B(x,y)$, where $c \in \{R,G,B\}$.

Suppose that given a color image $f_c(x,y)$, letting the area of the image be $A(r)$, $A(r)$ is the sum of the areas where the gray value is less than r, then the probability density $P(r)$ can be expressed as:

$$P(r) = \lim_{\Delta r \to 0} \frac{A(r+\Delta r) - A(r)}{\Delta r \bullet A} \tag{6}$$

Here, $\int_{\min}^{\max} P(r)dr = 1$. For a discrete digital color image $f_c(m,n)$, let the gray value of a single channel be $r_1, r_2, \dots, r_{k-1}$, then, the corresponding probability $P_c(r_i)$ can be expressed as:

$$P_c(r_i) = \frac{N_i}{N_{total}} \quad (7)$$

Where N_i denotes the number of pixels with gray value r_i, and N_{total} represents the total number of pixels in the image, $i = 0,1,2,\ldots,k-1$, $c \in \{R,G,B\}$ and $\sum_{i=0}^{k-1} P_c(r_i) = 1$.

For a color digital image, the origin moment of k-order histogram of a certain channel can be defined as:

$$m_k = \int r^k P_c(r)dr \quad (8)$$

and the central moment of k-order is defined as:

$$u_k = \int (r-\bar{r})^k P_c(r)dr \quad (9)$$

Here, $k = 0,1,\ldots$, and $\bar{r} = \frac{m_1}{m_0}$.

According to the definition of the central moment, the normalized central moment of the histogram can be obtained:

$$\eta_k = \frac{u_k}{u_0^{k+1}} \quad (10)$$

Similar to Hu's seven moment invariants, according to the normalized central moment invariants, the following four histogram moment invariants are proposed, which are invariant to translation, rotation and scaling.

$$h_1 = \frac{u_4}{u_2^2} \; h_2 = \frac{u_5}{u_2 u_3} \; h_3 = \frac{u_6}{u_3^2} \; h_4 = \frac{u_7}{u_3 u_4} \quad (11)$$

In order to improve the stability and reliability of histogram moment invariants, the four defined histogram moment invariants are modified, firstly, a gray correlation coefficient ρ is defined as follow:

$$\rho = \frac{\sum_{x=1}^{m}\sum_{y=1}^{n}(f_1(x,y)-aver1)(f_2(x,y)-aver2)}{(\sum_{x=1}^{m}\sum_{y=1}^{n}(f_1(x,y)-aver1)^2\sum_{x=1}^{m}\sum_{y=1}^{n}(f_2(x,y)-aver2)^2)^{1/2}} \quad (12)$$

Where $f_1(x,y)$ is the gray value of the original image, and aver1 is the gray mean value of the original image, $f_2(x,y)$ is the gray value of the image to be detected, and aver2 is the gray mean value of the image to be detected.

The modification version of histogram moment invariants are defined as:

$$\phi_1 = h_1/\rho, \phi_2 = h_2/\rho, \phi_3 = h_3/\rho, \phi_4 = h_4/\rho \quad (13)$$

IV. PROPOSED ZERO-WATERMARKING SCHEME

In this section, we will propose a zero-watermarking scheme to protect the copyright of color images. Our scheme consists of two basic stages: Zero watermark registration stage (watermark generation stage) and zero watermark detection or verification stage. A step-by-step description of these two phases is provided in the following sections.

A. Design of recovery algorithm against cropping and smearing attacks

In this subsection, we mainly introduce the implementation of recovery algorithm against cropping and smearing attacks, according to Eq. (1), it can be seen that:

$$V_{n\times m} = W_{n\times r} H_{r\times m} \quad (14)$$

letting $V = [v_1, v_2, \cdots, v_m]$, and $H = [h_1, h_2 \cdots, h_m]$, then

$$V_i = Wh_i \quad (15)$$

where v_i is the *i*-th column of V and h_i is the *i*-th column of H. it can be seen that each column of H matrix factor corresponds to the corresponding column of the original non-negative matrix V.

Letting $V' = [v_{k1}, v_{k2}, \cdots, v_{kt}]$, which is made up of any T columns of the V, here k1,k2,⋯kt∈[1,m], then:

$$V' = W[h_{k1}, h_{k2,} h_{k3,} \cdots, h_{kt}] \quad (16)$$

Letting $H' = [h_{k1}, h_{k2}, \cdots, h_{kt}]$, then, we can obtain: W, furthermore, W can be expressed as follows:

$$W = V'[H']^{-1} \quad (17)$$

It can be seen from the above description that when the original image matrix V is subjected to cropping or smearing attack, the whole base matrix W can still be recovered from the remaining partial matrix V. In order to make the base matrix W have a unique solution, the minimum rank of coefficient matrix V should be equal to the dimension of NMF decomposition, i.e. T≥ r.

B. Zero-watermark registration

The goal of this stage is to generate a verification message called zero watermark from the original host image, which is necessary for copyright protection.

Let $I_{M\times N}^{(RGB)}$ be a color image, size of $M \times N$, in the experiment, $M = N = 512$, and $b_k^{(c)}$ represents the block image or sub-image for each single-channel of $I_{M\times N}^{(RGB)}$, and in our scheme, let L represents a binary logo image, size of 32×32.The registration procedure of the proposed is summarized as follows:

a) Divide each channel of the color host image into 32×32 blocks, noted as $b_k^{(c)}$. In this paper, the color host image $I_{M\times N}^{(RGB)}$ was sized 512 ×512.

Therefore, when we divided the original image into 32 × 32 blocks, $k = 1, 2, 3...16*16$.

b) The four modified version HIMs of each single-channel sub-block image $b_k^{(c)}$ of the color host image are calculated, respectively, and the vector $\vec{A}$ is formed after taking the modulus, i.e., $\vec{A} = \{\{\phi_{c,b_1}^{(1)}, \phi_{c,b_1}^{(2)}, \phi_{c,b_1}^{(3)}, \phi_{c,b_1}^{(4)}\}, \{\phi_{c,b_2}^{(1)}, \phi_{c,b_2}^{(2)}, \phi_{c,b_2}^{(3)}, \phi_{c,b_2}^{(4)}\},$ $...\{\phi_{c,b_{16\times16}}^{(1)}, \phi_{c,b_{16\times16}}^{(2)}, \phi_{c,b_{16\times16}}^{(3)}, \phi_{c,b_{16\times16}}^{(4)}\}\}, \phi_{c,b_i}^{(n)} = \{\phi_{R,b_i}^{(n)}, \phi_{G,b_i}^{(n)}, \phi_{B,b_i}^{(n)}\}$ here, $c \in \{R, G, B\}$, and $n = 1, 2, 3, 4$, represents 4 numbers of modified version HIMs.

c) Using the mean value of the $\phi_{R,b_i}^{(n)}$, $\phi_{G,b_i}^{(n)}$ and $\phi_{B,b_i}^{(n)}$ to construct vector $\vec{B} = \{\tilde{\phi}_{b_1}^{(n)}, \tilde{\phi}_{b_2}^{(n)}, ...\tilde{\phi}_{b_{16\times16}}^{(n)}\}$, $n = 1, 2, 3, 4$, then, binarize the feature vector $\vec{B}$ to obtain the binary feature vector $\vec{C} = \{C_1, C_2, ...C_{32\times32}\}$ as follows:

$$C(p) = \begin{cases} 1, & B(p) \geq T \\ 0, & B(p) < T \end{cases} \quad (1 \leq p \leq 32 \times 32) \qquad (18)$$

here, T is the median of a vector $\vec{B}$, furthermore, a feature image L_F size of 32×32 is constructed by feature vector extraction computing method, i.e., transform one-dimensional data vector $\vec{C}$ into a digital image matrix size of 32×32.

d) Scramble the logo binary image $L_{32\times32}$ using the affine transform scramble to generate the scrambled logo L_s, The parameter of the affine transform are noted Key. This step enhances the proposed algorithm security.

e) Generate the zero-watermark image by applying the operation XOR between the scrambled logo L_s and the binary feature image L_F as follows:

$$S_{32\times32} = XOR(L_s, L_F) \qquad (19)$$

Finally, the zero-watermark $S_{32\times32}$ and the security Key can be stored in the Intellectual Property Rights database (IPR).

C. Zero-watermark detection

To illustrate the detection process of the copyright of a protected color image information, it is essential to know the security information {$S_{32\times32}$, Key}. The zero-watermark detection procedure is described as follows:

a) If the detected image is attacked by cropping or smearing operation, the whole W matrix of the detected image is reconstructed by the local remaining matrix of uncropping W and the corresponding H matrix, and then the recover image V matrix is further obtained. Otherwise, this step can be omitted.

b) Divide each channel of the protected color image $\tilde{I}_{M\times N}^{(RGB)}$ into 32×32 blocks, noted as $\tilde{b}_k^{(c)}$, here, $k = 1, 2, 3...16*16$, then, the four modified version HIMs of each single-channel sub-block image $\tilde{b}_k^{(c)}$ of the protected color image are calculated and computing the modulus for the constructed vector $\vec{A}^*$, moreover, taking the mean value of the elements in vector $\vec{A}^*$ to construct vector $\vec{B}^*$, which is similarly as zero-watermark registration.

c) Generation of the binary feature image L_F^*, the specific process is as follows: firstly, convert the feature vector $\vec{B}^*$ into a binary feature vector $\vec{C}^*$, then, rearrange the feature vector $\vec{C}^*$ into a 2D image L_F^* of size 32×32.

d) Making use of the zero-watermark $S_{32\times32}$ and the binary feature image L_F^* to recover the scrambled logo binary image L_s^* by applying XOR operation as follows:

$$L_s^* = XOR(S_{32\times32s}, L_F^*) \qquad (20)$$

e) Use the affine inverse transform with the security Key to recover the logo binary image $L_{32\times32}$ by descrambling the scrambled logo L_s^*.

V. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, a series of experiments and their analysis for the proposed zero-watermarking methodology is conducted via a set of four standard color images of size 512 × 512 pixels selected from common image processing datasets and a binary logo of size 32 × 32 bits. These images are shown in Fig. 1.

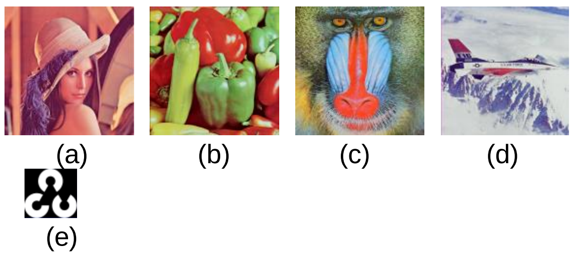

Fig. 1. (a) - (d) columns left to right show color images of "Lena", "Peppers", "Baboon", "Airplane, respectively. (e) The binary logo.

To verify the effectiveness of the proposed zero-watermarking methodology based on multi-channel for resisting image cropping or smearing attacks, this subsection describes the implementation and results of three groups of experiments. The first experiment investigated the robustness of the algorithm to various strongly cropped and randomly smeared images, and visualized the results of different cropping and smearing ratios on the Lena host color image. The second experiment examined the performance of the proposed zero-watermarking system on common image processing. The third experiment is to test the robustness for resisting rotation and scaling geometric attacks. Finally, the proposed zero-watermarking scheme is examined for various large-scale cropping, smearing attacks, geometric attacks, and against various common digital image processing attacks such as: Gaussian noise, Salt & pepper noise, median filtering, average filtering, JPEG compression, histogram equalization. To evaluate the performance of the zero-watermarking methodology, we adopt Bit Correctness Rate (BCR) [12] to measure the similarity between the original logo image L and recovered logo image *L**. BCR is defined as:

$$BCR = \frac{N_c}{N_{sum}} \tag{21}$$

Here, N_c represents the numbers of correct recovered bits of the logo binary image, and N_{sum} denotes the whole length of the logo binary image. BCR equal to 1means that verified logo image and original one are identical.

Experiment 1: Although the existing anti-geometric attack watermarking algorithms are effective against traditional geometric transformations (rotations, scaling, translations, or affine transformations) and conventional signal processing (noise adding, lossy compression, and image filtering), the information loss from strong cropping and shearing attacks have been rarely investigated in this field. Some of the robust watermarking algorithms can extract the watermark information to a certain extent after weak cropping (information loss < 20%), but cannot recover the watermark information after large-scale information loss (strong cropping or shear attacks). In such cases, the algorithms are invalid. Therefore, the cropping or smearing attacks are the most difficult problems in digital watermarking. In this experiment, the "Lena" color image was cropped by different ratios (20% , 50% , 75% , and 85%) on different regions of the image. The image was also randomly smeared at ratios of 26% , 78% , and 85% . Table1 shows the cropped and smeared images and their corresponding extracted logo binary images and BCR values. Unlike the zero-watermarking algorithm of Xia et al. [5], the proposed zero-watermarking scheme based on the NMF and modified version HIMs effectively detected the watermark and the BCR value can reach above 0.9, even on the image cropped by 85%. Thus, the proposed scheme is suitable for real image-copyright protection of large-scale cropped or smeared images.

TABLE 1: The logo recovered from the cropping or smearing attacked "Lena" color image

Host image				
Attacks	Parameters	Attacked images	Logo recovered image	BCR
Cropping	Upper-right cropping area:20%			0.9988
Cropping	Columns cropping area:50%			0.9922
Cropping	Rows cropping area:75%			0.9883
Cropping	Upper-right Cropping area:85%			0.9668
Smearing	Smearing area:26%			0.9922
Smearing	Smearing area:78%			0.9766
Smearing	Smearing area:85%			0.9125

Experiment 2: During network transmission, images are highly vulnerable to noise interference. In this experiment, the original color image was tested under attacks by Gaussian white noise with a variance of 0.001, salt and pepper noise with a density of 5%, and speckle noise with a variance of 0.04. As noise interference is usually removed by filtering operations, filtering (with consequent loss of image pixels) is another frequently encountered attack in image processing and pattern recognition. In the experiment, the original color host image was subjected to median and average filtering with a 5×5 window. Furthermore, images in network transmission, are frequently processed by JPEG compression and histogram equalization. JPEG compression causes pixel losses, and histogram equalization will change the distribution of image histogram. During this experiment, the histogram equalization was set to the default in Matlab2013a's software environment, and the JPEG compression ratio was set to 60. For each color image, the zero-watermark is first generated by following the steps in subsection 4.2, then the color image is attacked either by different common image processing attacks. Then the binary logo is retrieved by following the steps in subsection 4.3. Finally, the average BCR values of the recovered logos are calculated using Eq. (21). Table 2 shows the related information for different types of image attacks and Tables 3 and 4 compares the results of the proposed zero-watermarking scheme and other schemes (the direct graying-based method [17] and the single channel-based method [18]). The proposed algorithm was highly robust and outperformed the two established schemes.

TABLE 2: The related information for different types of image attacks

Types of image attacks	Parameters
Gaussian noise	Mean value: 0, variance:0.001
Salt & peppers noise	Noise intensity percentage: 5%
Median filtering	Filter window size: 5 × 5
Average filtering	Filter window size: 5 × 5
Gaussian blur	Default in Matlab2013a
JPEG compression	Compression quality:60
Histogram equalization	Default in Matlab2013a

TABLE 3: Typical results of images subjected to common image processing attacks

Attacks	BCR				
	Lena	Baboon	Airplane	Peppers	Average
Gaussian noise	0.9609	0.9727	0.9395	0.9492	**0.9555**
Salt &peppers noise	0.8242	0.9004	0.8066	0.8008	**0.8330**
Median filtering	0.9590	0.9283	0.9355	0.9316	**0.9386**
Average filtering	0.9297	0.9121	0.9219	0.9297	**0.9234**
Gaussian blur	0.9336	0.9258	0.9375	0.9355	**0.9331**
JPEG compression	0.9395	0.9590	0.9688	0.9315	**0.9510**
Histogram equalization	0.9219	0.9355	0.8281	0.9043	**0.8975**

TABLE 4: Comparison of experimental results under different image processing attacks

Attacks	*BCR*		
	Direct graying-based method [17]	Single channel-based method [18]	The proposed method
Gaussian white noise	0.9015	0.9252	0.9555
Salt & Peppers noise	0.8110	0.8032	0.8330
Median filtering	0.9216	0.9112	0.9386
Average filtering	0.9022	0.9104	0.9234
Gaussian blur	0.9031	0.9004	0.9331
JPEG compression	0.9210	0.9012	0.9510
Histogram equalization	0.8536	0.8275	0.8975

Experiment 3: The most frequently encountered geometric attacks on color host images are rotation and scaling. These attacks change the pixel positions in the image and increase the difficulty of watermark detection. In the anti-rotation experiment, the host color image was rotated by 45, 90, 135, and 180. In the anti-scaling experiment, the scaling parameters were varied as 0.9, 1.2, 1.5. Fig. 2 shows the experimental results of images subjected to rotation and scaling attacks. In the anti-rotation and anti-scaling experiments, we find that the zero-watermarking algorithm proposed in this paper, has good detection accuracy for cropping or smearing attacks, as well as conventional image processing, and has good robustness to rotation and scaling transformation in geometric attacks. Therefore, the proposed scheme has a certain practical value for digital image copyright protection.

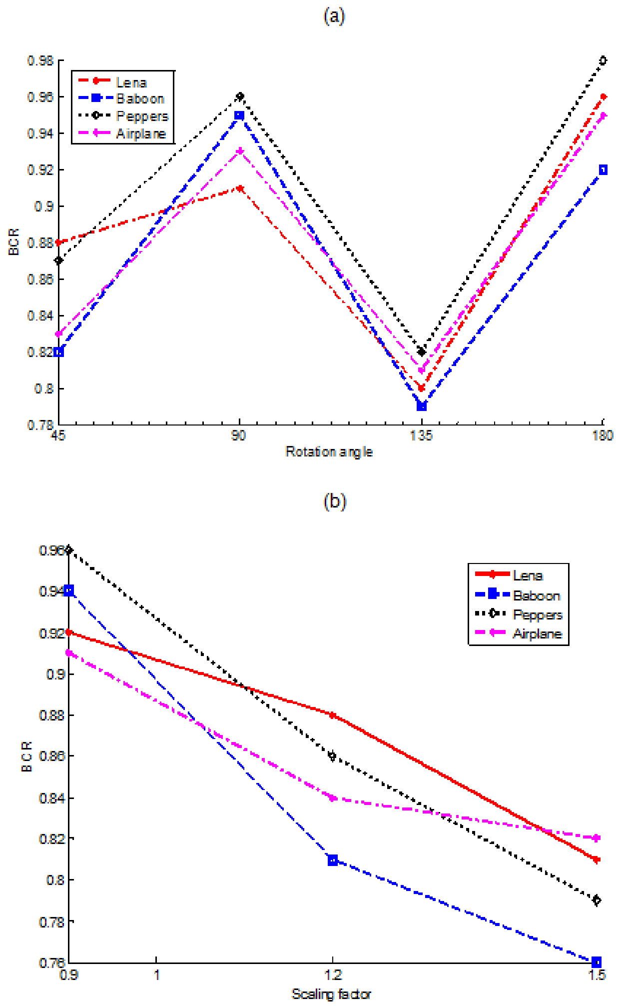

Fig. 2. Experimental results of images subjected to rotation and scaling attacks

VI. Conclusions

In this paper, we proposed a novel zero-watermarking algorithm, to protect color images, based on NMF and modified version of HIMs. The proposed algorithm is very robust against cropping or smearing attacks, especially large-scale cropping operation. At the same time, the proposed algorithm also has good robustness to geometric transformation attacks and conventional image processing operations. In addition, since we scramble the binary logo image before generating zero-watermark, the security of zero-watermarking algorithm is enhanced. thus the proposed zero-watermarking algorithm has an important practical value in the copyright protection of color images. In future work, we will extend this algorithm to frequency domain (e.g., wavelet transform domain) to enhance the performance of image noise resistance. In addition, we will try to apply the feature-extraction method used in this paper to the related fields such as target detection, image segmentation, image classification and so on.

Acknowledgment

The authors would like to thank the anonymous referees for their valuable comments and suggestions. This work was supported by the Science Foundation of the Shaanxi Key Laboratory of Network Data Analysis and Intelligent Processing (Grant No. XUPT-KLND201901), Shaanxi Province of Key R & D project (Grant No. 2020GY-051), Weinan regional collaborative innovation development research project (Grant No. WXQY001-001 and WXQY002-007) and Shaanxi Provincial Department of Education project (Grant No. 20JS044).

References

[1] Wang C, Wang X, Xia Z C, et al. Ternary radial harmonic Fourier moments based robust stereo image zero-watermarking algorithm-ScienceDirect[J]. Information Sciences, 2019, 470:109-120.

[2] Xia Z, Wang X, Li X, et al. Efficient copyright protection for three CT images based on quaternion polar harmonic Fourier moments[J]. Signal processing, 2019, 164(11):368-379.

[3] Xiang S, Kim H J, Huang J. Invariant Image Watermarking Based on Statistical Features in the Low-Frequency Domain[J]. IEEE Transactions on Circuits & Systems for Video Technology, 2008, 18(6):777-790.

[4] Du W, Wang D, Li S, et al. Histogram-based image watermarking algorithm using visual perception characteristics[C]//The Second International Conference on Image, Video Processing and Artificial Intelligence. 2019.

[5] Xia Z, Wang X, Wang M, et al. Geometrically Invariant Color Medical Image Null-Watermarking Based on Precise Quaternion Polar Harmonic Fourier Moments[J]. IEEE Access, 2019.

[6] Hosny K M, Da Rwish M M. Robust color image watermarking using invariant quaternion Legendre-Fourier moments[J]. Multimedia Tools and Applications, 2018, 77(2):1-24.

[7] Lin C, Pan J S, Liao B Y. Parity Modulation Based Watermarking Resisting to Cropping[C]// International Conference on Innovative Computing. IEEE, 2007.

[8] Wen Q, Sun T F, Wang S X. Concept and Application of Zero-Watermark[J]. Acta electronica sinica, 2003.

[9] Liu G, Wang Q, Wu L, et al. Zero-watermarking method for resisting rotation attacks in 3D models[J]. Neurocomputing, 2021, 421:39-50.

[10] Xia Z, Wang X, Han B , et al. Color image triple zero-watermarking using decimal-order polar harmonic transforms and chaotic system[J]. Signal Processing, 2021, 180:178-196.

[11] Xia Z, Wang X, Li X, et al. Efficient copyright protection for three CT images based on quaternion polar harmonic Fourier moments[J]. Signal processing, 2019, 164(Nov.):368-379.

[12] Lee D D, Seung H S. Learning the parts of objects by non-negative matrix factorization[J]. Nature, 1999, 401(6755):788-791.

[13] Zhang T, Fang B, He G, et al. Face Recognition Using Topology Preserving Nonnegative Matrix Factorization[C]// International Conference on Computational Intelligence & Security. IEEE Computer Society, 2007.

[14] Liu W, Zheng N, You Q. Nonnegative matrix factorization and its applications in pattern recognition[J]. Chinese Science Bulletin, 2006, 51(1):7-18.

[15] Hosny K M, Darwish M M. New set of multi-channel orthogonal moments for color image representation and recognition, Pattern Recognition, 2019, 88:153-173.

[16] Singh C, Singh J. Multi-channel versus quaternion orthogonal rotation invariant moments for color image representation[J]. Digital Signal Processing, 2018, 78: 376-392.

[17] Jin N R, Lv X Q, Gu Y, et al. Blind watermarking algorithm for color image in Contourlet domain based on QR code and chaotic encryption[J]. Packaging engineering, 2017, 38(15): 173-178

[18] Hong Y L, Qie G L, Yu H W, et al. A contrast preserving color image graying algorithm based on two-step parametric subspace model[J]. Frontiers of Information Technology & Electronic Engineering, 2017 (11): 102-116.