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Zero Watermarking Scheme Based on U and V Matrices of Quaternion Singular Value Decomposition for Color Images

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Abstract. *This paper presents a novel zero watermarking for color image copyright protection based on the U and V matrices of Quaternion Singular Value Decomposition (QSVD). In this scheme, we represent a color image with a quaternion matrix, so that it can deal with the multichannel information in a holistic way. Then the pure quaternion array of the input color image is partitioned into non-overlapping blocks. Through applying QSVD to each block, we can obtain its U and V matrices. We take the first column of the U matrix and V matrix of each block as research objects and construct the zero watermarks using the mean square deviation relationship between the squares of norms of the quaternion elements in the research objects. In addition, we have done a lot of experiments to verify the robustness of the algorithm and the advantages of other algorithms are compared. The experimental results are given to demonstrate that the proposed algorithm outperforms existing schemes in terms of robustness.*
Keywords: Zero-Watermarking, Copyright Protection, Quaternion Singular Value Decomposition (QSVD), U matrix, V matrix

1. **Introduction.** With the advent of the mobile Internet and big data Era the digital multimedia information has increased dramatically. As the digital media can be easily and quickly spread and distributed through the Internet, How to protect the intellectual property rights of multimedia and prevent counterfeiting in the internet and big data environment has become an urgent problem. As a new security measure, digital watermarking has been widely used in digital image copyright protection[1][2]. Technically, a watermarking algorithm includes two parts: constructing or embedding algorithm and

watermark detecting algorithm. Watermarks can be embedded in the pixel domain or a transform domain. Digital watermarking technology embeds some identifying information into digital host media (including multimedia documents, software, etc.) directly or indirectly and does not affect the value of the original carrier, which is not easy to detect and modify again [3].

Copyright protection generally requires digital watermarking to have the following characteristics: robustness and invisibility . When the watermark information is embedded into the host information, it is inevitable to make the conflict between robustness and invisibility[19][20].. The invisibility requires that the information embedded as little as possible to change the host data, while the robustness hopes that the watermark can resist some attacks by embedding the information as much as possible. For the sake of solving this problem, we wish we could construct a watermarking without modifying the host information. In this case, people put forward the concept of zero watermarking [4]. Zero watermarking is a novel digital watermarking technique different from general digital watermarking in its use of the characteristics of the original image to construct the watermark, without embedding any watermark in the image, so it does not modify the original image [5]. The zero watermarking algorithms have the following two advantages over the traditional watermarking methods. First of all, they do not cut down the quality of the host carriers, and therefore, they have better imperceptibility. Secondly, they pay close attention to constructing the zero-watermarking information through the use of import features the host carriers instead of embedding the watermark.

Nowadays, many researchers have studied zero watermarking technology and proposed some good algorithms. For example, in [6], Wen et al. proposed a zero watermarking algorithm using high-order cumulants to protect the copyright of the host medias. The algorithm can resist the attacks of common image processing including slight rotation and have good performance. Chang and Lin [7] proposed an adaptive watermark mechanism to protect the copyright. This approach generates a verification map through using Sobels edge detection. In addition, in order to enhance the robustness in the spatial domain, this approach adjusts the strength of watermarks through a threshold. In [9], in the singular value decomposition domain transformed by contourlet, Vellaisamy and Ramesh proposed a zero watermarking method can resist an inversion attack for original medical image. An effective zero watermarking method [8] was proposed to improve the robustness and protect the copyright of the original image using an -trimmed mean algorithm and SVM. Based on Bessel-Fourier moments, a zero watermarking system that can resist common image processing attacks and geometric attacks was presented by Gao and Jiang in [10]. On account of the generalized Arnold transform, Lin et al. proposed a new zero watermarking method in [11].

From the above methods, we can see that these algorithms are mostly developed for grayscale images rather than color images. In our daily life, the color images are frequently used. Because the color images contain more information than greyscale images, it is very important to develop zero watermarking methods for resisting common image processing attacks. Because of the strong spectral relation between each color channel of the color image, if a color pixel is processed as a whole, the spectral links between the color channels of the pixel will run through the whole process of operation, we use the pure quaternion to represent the color image. In this paper, a new zero watermarking for copyright protection of color images based on the U and V matrices of QSVD is proposed. The proposed method represents the color image with a quaternion matrix, so that it can deal with the multichannel information in a holistic way. The pure quaternion array of color image is partitioned into non-overlapping blocks. Through applying QSVD to each block, we can obtain its U and V matrices. We take the first column of the U matrix and V matrix of each block as research objects and construct the zero watermarks using the mean square deviation relationship between the squares of norms of the quaternion elements in the research objects. In addition, we have done a lot of experiments to verify the robustness of the algorithm and the advantages of other algorithms compared. The experimental results are given to demonstrate that the proposed algorithm outperforms existing schemes in terms of robustness.

In the rest part, this paper is organized as follows. Section 2 introduces the basic theory related to the proposed algorithm. Section 3 detailly describes our watermark embedding and extraction algorithms. Section 4 shows the experimental results and gives the corresponding analysis. Section 5 draws the final conclusion.

2. **The basic theory.**

2.1. **Quaternion Representation of A Color Image.**

The quaternion [12]is a simple super complex, which was firstly put forward by Hamilton in 1843. A quaternion is composed of a real number and three imaginary numbers, which are defined as (1):

$$q = q_1 + q_2 * j + q_3 * j + q_4 * k \tag{1}$$

Where q_1, q_2, q_3,q_4 are real numbers, and i, j, k are complex operators which satisfy the following basic properties:

$$i^2 = j^2 = k^2 = -1, ij = -ji = k, jk = -kj = i, ki = -ik = j \tag{2}$$

If a quaternion q ∈ Q(Q denotes the quaternion domain) has a zero scalar part (q_1=0),then q is called a pure quaternion. The definition of the norm of q is shown as follows:

$$\|q\| = \sqrt{q_1^2 + q_2^2 + q_3^2 + q_4^2} \tag{3}$$

When a pure quaternion q has a unit norm, the quaternion is called a unit pure quaternion. Then, the Euler equation definition of a unit pure quaternion is shown as follows:

$$e^{\mu\phi} = \cos\phi + \mu \sin\phi \tag{4}$$

Where μ represents any unit pure quaternion, we can get: : $e^{\mu\phi} = 1$.

In [18], Sangwine proposed to represent the three color components (R, G, B) of a color image by the three imaginary parts (q_2, q_3,q_4) of a pure quaternion respectively, which isshown as follows:

$$IM(x, y) = I_R(x, y)i + I_G(x, y)j + I_B(x, y)k \tag{5}$$

Where I_R(x, y) , I_G (x, y) and I_B (x, y) represent the three primary components (R, G, B) of one pixel of a color image respectively, and i, j, k represent the complex operators. The pure quaternion matrix has been utilized to represent the color image as the research object increasingly in the color image processing field. It is easy to see that the benefit of representing a color image as a pure quaternion matrix is that we can research the color image as a whole without losing any chromatographic information.

For better operation of the pure quaternion matrix, each pure quaternion representing the pixel of the color image is often normalized, which is shown as follows.

$$IM(x, y) = (I_R(x, y)i + I_G(x, y)j + I_B(x, y)k)/256 \tag{6}$$

2.2. **Quaternion Singular Value Decomposition.** Given a matrix A, its formula [11] of QSVD (Quaternion Singular Value Decomposition) can be represented as follows.

$$A = U * S * V \tag{7}$$

Where S=$diag(\sigma_1, \sigma_2, ...\sigma_n)$, and $\sigma_1 \geq \sigma_2 \geq ... \geq \sigma_n \geq 0$, $\sigma_1, \sigma_2, ..., \sigma_{n-1} and \sigma_n$ are n eigenvalues of the matrix A .On the basis of Eq. (5), a color image with m rows and n columns can be represented by a pure quaternion matrix which can be shown as follows:

$$IMQ = (q_{ij})_{m\times n}, q_{ij} \in Q \tag{8}$$

The pure quaternion theory provides many new theories and methods for color image processing. The QSVD is an orthogonal transformation of diagonalization of the quaternion matrix. The singular values obtained by decomposition consist of a nonnegative real number vector whose length is equal to the rank of the matrix. It has the ability to comprehensively reflect the energy and color characteristics of color images. Because these new theories and methods treat the three primary components(R,G,B) of a color image in a holistic way, the map relationship of intrinsic chromatographic of the three primary components (R,G,B) could be retained. For constructing the zero watermarking for a color image, a pure quaternion matrix representing a color image should be transformed by QSVD as follows:

$$QSVD(IMQ) = [USV] \tag{9}$$

Where S is a diagonal matrix represented as follows:

$$S = diag(\sigma_1, \sigma_2, ...\sigma_n) \tag{10}$$

2.3. **Selection of the Best Coefficient Pair.** In order to select the best coefficient pair to construct the zero watermarks, we have done a series of experiments.

Firstly, we calculate the square value of norm of each quaternion of the U matrix and the square value of norm of each quaternion of the first column of the V matrix by experiments. Table1 shows the above calculation results of the U matrix and the first column of the V matrix which are obtained by applying QSVD to an example block.

From Table 1, we can see that the difference among the square of norms of each quaternion in the first column of the U matrix is the smallest, as well as the difference among the square of norms of each quaternion in the first column of the V matrix. In order to explore further the relationship of the quaternions in each column of the U matrix and the first column of the V matrix, we shall calculate the mean square deviation values of the square of norms of the quaternions in each column of the U matrix and the first column of the V matrix which are obtained by applying QSVD to the block attacked by the common JPEG compression, filtering and other processing. The computing results are shown in Table 2, where $(\varepsilon_\Delta^i)^2$ is shown as follows:

$$(\varepsilon_\Delta^i)^2 = \frac{\sum_{j=1}^{8}\left(|\Delta(j,i)|^2 - Me_i^2\right)^2}{8} \tag{11}$$

Where Me_i^2 is defined as:

$$Me_i = \frac{\sum_{j=1}^{8}|\Delta(j,i)|^2}{8} \tag{12}$$

Where $\Delta = U$ or $\Delta = V$, i = 1,2,3,...8.

From Table 2, we can see that under the same image processing operation, the mean square deviation values of $(\varepsilon_U^1)^2$ and $(\varepsilon_V^1)^2$ is the smallest, which illustrates further the difference among each quaternion in the first column of the U matrix is the smallest as well as the difference among each quaternion in the first column of the V matrix. In addition, we can also see that the polarity between $(\varepsilon_U^1)^2$ and $(\varepsilon_V^1)^2$ is stable when different image processing attacks are applied to the image respectively. Therefore, based on the above two aspects, we choose$(\varepsilon_U^1)^2$ and$(\varepsilon_V^1)^2$ to construct the zero watermark to protect the copyright of color images.

TABLE 1. The square of norms of each quaternion in the U matrix and the first column of the V matrix

	$\lvert U(i,1)\rvert^2$	$\lvert U(i,2)\rvert^2$	$\lvert U(i,3)\rvert^2$	$\lvert U(i,4)\rvert^2$	$\lvert U(i,5)\rvert^2$	$\lvert U(i,6)\rvert^2$	$\lvert U(i,7)\rvert^2$	$\lvert U(i,8)\rvert^2$	$\lvert V(i,1)\rvert^2$
$i=1$	0.1368	0.1258	0.0520	0.0340	0.0020	0.0197	0.0566	0.5735	0.1326
$i=2$	0.1417	0.1018	0.0370	0.0250	0.0350	0.3301	0.2644	0.0660	0.1405
$i=3$	0.1416	0.0908	0.0120	0.0090	0.0240	0.1399	0.3362	0.2474	0.1443
$i=4$	0.1439	0.0418	0.0020	0.0250	0.1410	0.3799	0.2405	0.0624	0.1360
$i=5$	0.1315	0.0099	0.2730	0.3520	0.0710	0.0763	0.0506	0.0349	0.1239
$i=6$	0.1194	0.0975	0.2410	0.0760	0.3730	0.0340	0.0577	0.0017	0.1178
$i=7$	0.1017	0.2603	0.0140	0.2800	0.2920	0.0167	0.0285	0.0072	0.1065
$i=8$	0.0834	0.2722	0.3700	0.2000	0.0620	0.0033	0.0013	0.0068	0.0983

3. **Proposed Algorithm.** This section describes our color image zero watermarking technique based on the U and V matrices of Quaternion Singular Value Decomposition to protect the copyright of the original color images. The zero watermarking technique constructs the zero watermark based on the mean square deviation pair $(\varepsilon_U^1)^2$ and $(\varepsilon_V^1)^2$ of the first column of U_i and V_i .The constructing procedure and extracting procedure are illustrated by subsections 3.1 and 3.2 respectively.

TABLE 2. The influence of various image processing operations on the relationship of the mean square deviation values of the square of norms of the quaternions

	Original	*JPEG*	*Salt&Pepper*	*MedianFiltering*	*GaussianFiltering*
$(\varepsilon_U^1)^2$	4.25E-04	4.70E-04	5.47E-04	4.23E-04	4.60E-04
$(\varepsilon_U^2)^2$	0.0078	0.0094	0.00159	0.0076	0.0203
$(\varepsilon_U^3)^2$	0.0187	0.0254	0.00134	0.0200	0.0085
$(\varepsilon_U^4)^2$	0.0157	0.0148	0.01490	0.0180	0.0063
$(\varepsilon_U^5)^2$	0.0163	0.0270	0.01280	0.0172	0.0057
$(\varepsilon_U^6)^2$	0.0194	0.0177	0.01970	0.0448	0.0044
$(\varepsilon_U^7)^2$	0.0137	0.0161	0.01550	0.0383	0.0044
$(\varepsilon_U^8)^2$	0.0343	0.0093	0.03210	0.0397	0.0082
$(\varepsilon_V^1)^2$	2.37E-04	1.64E-04	3.17E-04	1.65E-04	3.23E-04

3.1. **Constructing Procedure.** In order to use the U and V matrices of QSVD transformation to construct a zero watermark for an original image, we explored the square of norms of the quaternions in each column of the U matrix and the first column of the V matrix as shown in Table 1. In addition, we also explored the mean square deviation pair $(\varepsilon_U^1)^2$ and $(\varepsilon_V^1)^2$ of each column of U_i and the first column of V_i.Based on our experiments, we choose $(\varepsilon_U^1)^2$ and $(\varepsilon_V^1)^2$ to construct the zero watermark to protect the copyright of color images.

The size of host color image I represented by quaternion is $m \times n$ .The pure quaternion matrix I is divided into non-overlapping block B_i which size is 32 × 32, where$1 \le i \le \left\lfloor \frac{m}{32} \right\rfloor \times \left\lfloor \frac{n}{32} \right\rfloor$ and $I = B_1 \cup B_2 \cup \cdots \cup B_{\lfloor m/32 \rfloor \times \lfloor n/32 \rfloor}$ The zero watermark W is a binary image

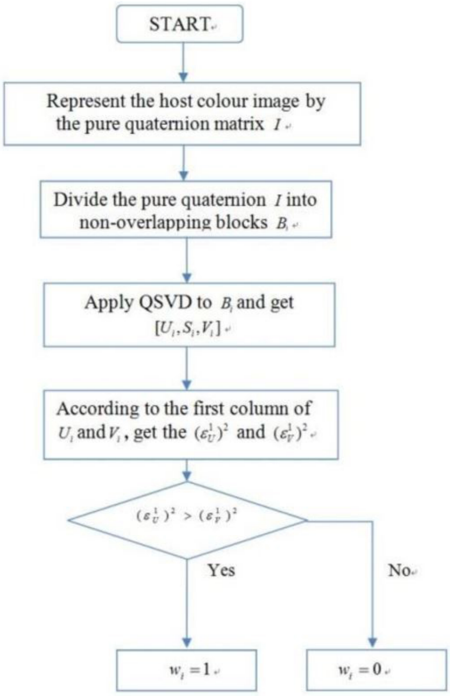

FIGURE 1. Overview of the constructing procedure

which size is $u \times v$ bits, where $W = (w_1, w_2, \cdots, w_{\lfloor \frac{m}{32} \rfloor \times \lfloor \frac{n}{32} \rfloor})$and $w_i \in \{1, 0\}$ Apply QSVD to B_i and get $[U_i, S_i, V_i]$. In order to construct the zero-watermarking to the host color image, we calculate the mean square deviation pair $(\varepsilon_U^1)^2$ and $(\varepsilon_V^1)^2$ of the first column of U_i and V_i . An overview of the constructing procedure is shown in Figure 1.The detailed constructing procedure is illustrated as follows:

Step 1: Using the normalized pure quaternion matrix I to represent the host color image.

Step 2: Divide the normalized pure quaternion matrix I into non-overlapping blocks B_i of size 32 × 32.

Step 3: Apply QSVD to B_i and get $[U_i, S_i, V_i]$, then obtain the first column of U_i and V_i

Step 4:According to the formula (11) and formula (12),Calculate the mean square deviation pair $(\varepsilon_U^1)^2$ and $(\varepsilon_V^1)^2$ of the first column of U_i and V_i.

Step 5: According to the value of the mean square deviation pair $(\varepsilon_U^1)^2$ and $(\varepsilon_V^1)^2$, the criteria that we construct the zero-watermarking in detail is as following:

if $(\varepsilon_U^1)^2 > (\varepsilon_V^1)^2$, $w_i = 1$; otherwise, $w_i = 0$.

3.2. **Extracting Procedure.** Our extraction process is very simple, which can be described in detail as follows:

Step 1: Represent the suspect color image by the normalized pure quaternion matrix I^* .

Step 2: Divide the color image I^* into non-overlapping blocks B_i^* of size 32 × 32.

Step 3: Perform QSVD to B_i^* and we get $[U_i^*, S_i^*, V_i^*]$, then obtain the first column of U_i^* and V_i^*.

Step 4:According to the formula (11) and formula (12),Calculate the mean square deviation pair $(\varepsilon_U^{1*})^2$ and $(\varepsilon_V^{1*})^2$ of the first column of U_i^* and V_i^*.

Step 5:Based on the mean square deviation pair $(\varepsilon_U^{1*})^2$ and $(\varepsilon_V^{1*})^2$, we can extract the zero watermark using the following criteria:

if $(\varepsilon_U^{1*})^2 > (\varepsilon_V^{1*})^2$, $w_i = 1$; otherwise, $w_i = 0$.

4. **Experimental Results and Analysis.** The performance of a digital watermarking scheme is commonly assessed in terms of the imperceptibility after watermark constructing and the robustness after watermark extraction. In this section, we will do a lot of experiments to evaluate the imperceptibility and the robustness of the proposed method and also compare with several existing schemes.

This section is divided into four parts. The first part introduces the objective evaluation principle. The second part introduces the similarity among the zero watermarks constructed in different images. The third part introduces the robustness results of the proposed algorithm. The fourth part compares the proposed al with other existing state-of-the-art algorithms. All of the experiments are developed in the MATLAB R2010b environment on a Lenovo laptop with a 2.6 GHz Intel Pentium processor and 8 GB of RAM. Eight well-known color test images widely used in image watermarking, i.e., Lena, Barbara, Mandrill, Airplane, Girl, House, Peppers, Sailboat, are used as the benchmark images of size 512 × 512 as shown in Figure 2.

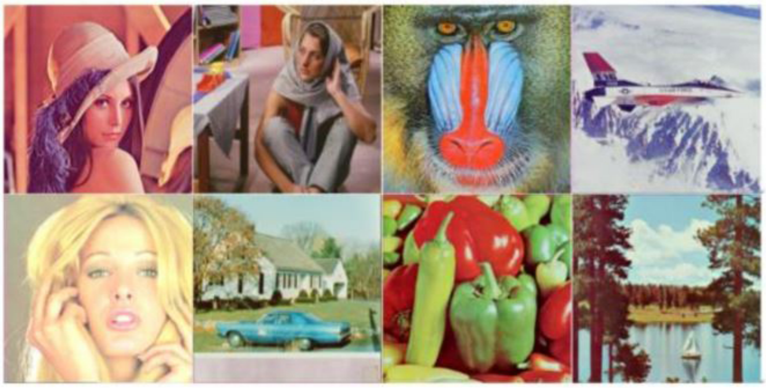

FIGURE 2. Eight benchmark images

4.1. **Evaluation Criteria.** The measures CPSNR (Color Peak Signal-To-Noise Ratio) and NC (Normalized cross-correlation) are often jointly used to evaluate the imperceptibility and robustness of the zero watermarking algorithms. The CPSNR value is used to measure the image quality of the watermarked image

Which is defined as follows:

$$CPSNR = 10\log_{10}\frac{255^2}{MSE}dB \tag{13}$$

Where the mean square error (MSE) is defined as follows:

$$MSE = \frac{\sum_{k=1}^{3}\sum_{u=1}^{A}\sum_{v=1}^{B}(x_{uv}^{k} - x_{uv}^{k'})^2}{3 \times A \times B} \tag{14}$$

Here, A and B respectively denote the height and width of the input color image, while x_{uv}^{k} and$x_{uv}^{k'}$ are the pixel values of the k-th color channel at the position (u,v) of the original image and the watermarked image respectively. In general, for a watermarked image, a higher CPSNR value implies a better image quality. In addition, NC is often used to measure the similarity between the extracted watermark and the original watermark, which is defined as follows.

$$NC = \frac{\sum_{i=1}^{m\times n} \overline{w_i \oplus w_i^{'}}}{m \times n} \times 100\% \tag{15}$$

Where $\oplus$ stands for the exclusive OR operator, while w_i and $w_i^{'}$, respectively denote the i-th bits of the original and extracted watermarks. Note that, the higher the NC value is the greater similarity between the original and extracted watermarks we will have.

4.2. **The similarity between zero watermarks in different images.** In order to testify thevalidity of the proposed zero watermarking algorithm, we do a lot of experiments to evaluate the similarity between zero watermarks in different images. The experimental results are shown in Table 3.

From Table 3, we can see that the maximum similarity value between different images is only 0.6211, which illustrates that different color image has different zero watermark and the similarity between zero watermarks in different images is low. Therefore, the proposed zero watermarking algorithm has good validity.

4.3. **The Experimental Results with Attacks.** In this part, a set of attack experiments are conducted to evaluate the robustness of the proposed algorithm. Various attacks are performed, including:

- JPEG Compression: compress the image with JPEG, QF(Quality Factor)=30,50,70,90.
- Cropping: replace the middle 1/16 of the watermarked image with zeros.
- Gaussian noise: add Gaussian white noise to the embedded image with $\mu = 0$ and variance $\sigma^2 = 0.001$, 0.005, 0.01, 0.1.
- Salt & pepper noise: add salt & pepper noise to the host image with a noise density den = 0.001,0.005,0.01.
- Histogram equalization: enhance the overall contrast of the host image, only applied to the luminance channel.
- Motion blurring: 2-D linear filtering by using a 1×9 pixel mask.
- Median filtering: apply the median filtering to the color image with the masks of 3×3, 5×5, 7×7.
- Mean filtering: apply the mean filtering to the color image with the masks of 3×3, 5×5, 7×7.

Table 3. The similarity values between zero watermarks in different images

	Lena	*Mandrill*	*Girl*	*Barbara*	*House*	*Peppers*	*Sailboat*	*Airplane*
Lena	1	0.4609	0.5898	0.5313	0.3984	0.5625	0.5313	0.4258
Mandrill	0.4609	1	0.4961	0.5000	0.4922	0.5000	0.4531	0.4727
Girl	0.5898	0.4961	1	0.5117	0.5039	0.5742	0.5352	0.5547
Barbara	0.5313	0.5000	0.5117	1	0.4766	0.5156	0.5156	0.5352
House	0.3984	0.4922	0.5039	0.4766	1	0.4609	0.5313	0.5430
Peppers	0.5625	0.5000	0.5742	0.5156	0.4609	1	0.4297	0.5039
Sailboat	0.5313	0.4531	0.5352	0.5156	0.5313	0.4297	1	0.6211
Airplane	0.4258	0.4727	0.5547	0.5352	0.5430	0.5039	0.6211	1

Figure. 3 shows the attacking results for the Lena image, Tables 4-10 list the attacking results for all test images.From Tables 4-10, we can see that the NC values are measured after watermark extraction under the aforementioned attacks. We can see that high robustness values can be obtained for most types of attacks. Especially, under the median filtering (3×3) attack and cropping (1/16) attack, the NC value of each image is 0.9961, that is to say, the original watermark is almost recovered. Moreover, different results are obtained for each image, which draws a conclusion that different structures of different images can influence the robustness to some extent. Beyond that, we discover that the proposed algorithm cannot effectively cope with the Rotate attack (3° ,5° ,7°) with the NC values of 0.7695,0.7031 and 0.6953 respectively.

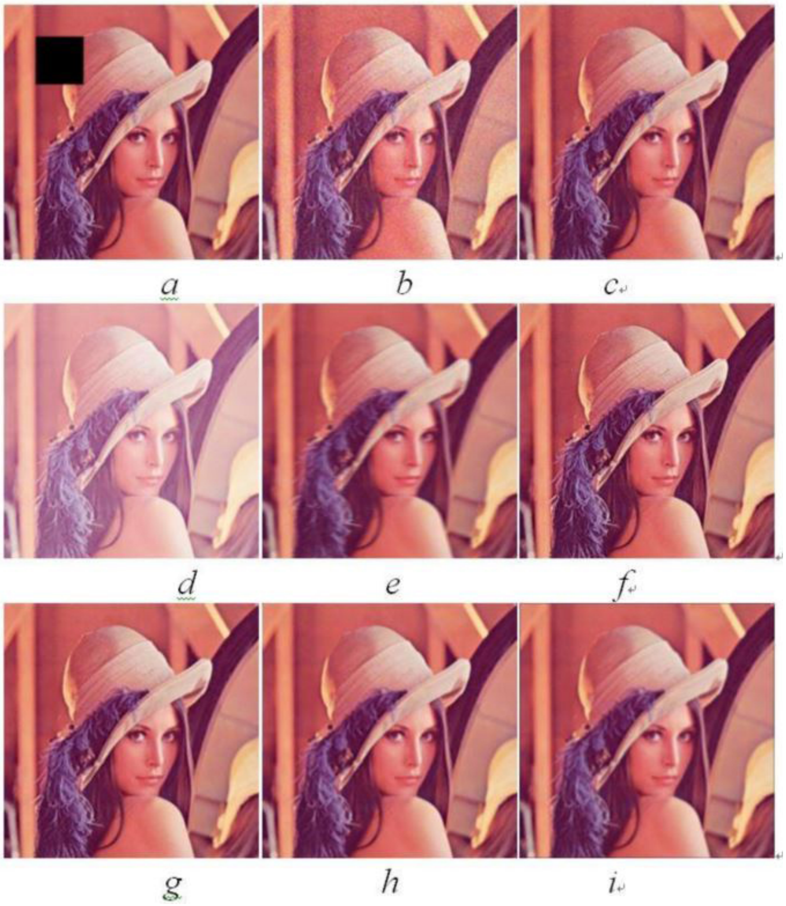

FIGURE 3. Watermarked images subject to different attacks: (a) Cropping; (b) Gaussian noise; (c) Salt & Pepper noise; (d) Histogram equalization; (e) Motion blurring; (f) Sharpening; (g) JPEG(70); (h) Median filtering(5×5); (i) Mean filtering (5×5)

TABLE 4. Results under JPEG attack

QF	$CPSNR$	NC
30	34.9000	0.9570
50	35.6583	0.9727
70	36.3942	0.9805
90	37.9835	0.9922

4.4. **Comparisons with State-of-the-art Methods.** In this section, we compare the proposed method with some existing state-of-the-art methods including Feng and Chen [16] and Pan et al. [17] through applying different common attacks on the watermarked

Table 5. Results under Gaussian noise attack

σ^2	$CPSNR$	NC
0.001	28.8140	0.9531
0.005	29.0105	0.9297
0.01	29.2345	0.9570
0.1	35.0273	0.9727

Table 6. Results under Salt& pepper noise attack

σ^2	$CPSNR$	NC
0.001	57.0696	0.9883
0.005	50.0893	0.9883
0.01	50.2899	0.9766

Table 7. Results under Median filtering attack

$mask$	$CPSNR$	NC
3×3	37.6124	0.9961
5×5	35.7095	0.9883
7×7	34.8527	0.9844

Table 8. Results under Mean filtering attack

$mask$	$CPSNR$	NC
3×3	36.1977	0.9375
5×5	34.3053	0.9219
7×7	33.3104	0.9063

color image. The comparison results are shown in Table 11. Through analysing the results in Table 11, we can confirm that the proposed method outperforms other approaches except for Pan et al.'s approach in terms of the mean Filtering (3×3) attack. With respect to the JPEG (90), Pan et al. 's method provides a greater watermarked image quality than any other method. With respect to the Gaussian noise attack, Feng and Chen's method provides a greater watermarked image quality than any other method. With regard to the histogramequalization, cropping, median Filtering, JPEG (70), Salt&Pepper noise and rotation attacks, our algorithm provides the strongest robustness

5. **Conclusion.** In this paper, a new zero watermarking for copyright protection of color images based on the U and V matrices through Quaternion Singular Value Decomposition (QSVD) is proposed. The proposed method represents the color image with a quaternion matrix, so that it can deal with the multichannel information in a holistic way. Then the pure quaternion array of color image is partitioned into non-overlapping blocks. Through applying QSVD to each block, we can obtain its U and V matrices. We take the first column of the U matrix and V matrix of each block as research objects and construct the zero watermarks using the mean square deviation relationship between the squares of norms of the quaternion elements in the research objects. In addition, we have done a lot of experiments to verify the robustness of the algorithm and the advantages of other algorithms compared. The experimental results are given to demonstrate that the proposed algorithm outperforms existing schemes in terms of robustness.

Table 9. Results under other image processing attack

$method$	$CPSNR$	NC
$Cropping(1/8)$	38.6054	0.9688
$Cropping(1/16)$	48.1478	0.9961
$Blurring$	33.6118	0.9492
$Brighten$	INF	0.9648
$Darken$	24.2806	0.9766
$Sharpen$	31.8853	0.9336

Table 10. Results under other image processing attack

$method$	$CPSNR$	NC
$Rotate3°$	24.4723	0.7695
$Rotate5°$	27.8716	0.7031
$Rotate7°$	27.5273	0.6953

Table 11. Comparisons of NC values among our and state-of-the-art methods

$Attacks$	$Panetal.$[17]	$FengandChen$[16]	$Ours$
$Cropping(1/16)$	0.9688	0.9928	0.9961
$Gaussiannoise(0.001)$	0.9488	0.9567	0.9531
$Rotate3°$	0.6012	0.7708	0.7695
$Salt\&Peppernoise(0.001)$	0.9688	0.9819	0.9883
$Histogramequalization(brighten)$	N/A	0.9501	0.9648
$Histogramequalization(darken)$	N/A	0.9603	0.9766
$MedianFiltering(3 \times 3)$	0.9688	0.9675	0.9961
$MeanFiltering(3 \times 3)$	0.9467	0.8992	0.9375
$JPEG(90)$	0.9934	0.9801	0.9922
$JPEG(70)$	0.9688	0.9545	0.9805

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