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Color image watermarking scheme based on quaternion Hadamard transform and Schur decomposition

Jianzhong Li[1] · **Chuying Yu**[2] · **B. B. Gupta**[3] · **Xuechang Ren**[4]

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Abstract Based on quaternion Hadamard transform (QHT) and Schur decomposition, a novel color image watermarking scheme is presented. To consider the correlation between different color channels and the significant color information, a new color image processing tool termed as the quaternion Hadamard transform is proposed. Then an efficient method is designed to calculate the QHT of a color image which is represented by quaternion algebra, and the QHT is analyzed for color image watermarking subsequently. With QHT, the host color image is processed in a holistic manner. By use of Schur decomposition, the watermark is embedded into the host color image by modifying the Q matrix. To make the watermarking scheme resistant to geometric attacks, a geometric distortion detection method based upon quaternion Zernike moment is introduced. Thus, all the watermark embedding, the watermark extraction and the geometric distortion parameter estimation employ the color image holistically in the proposed watermarking scheme. By using the detection method, the watermark can be extracted from the geometric distorted color images. Experimental results show that the proposed color image watermarking is not only invisible but also robust against a wide variety of attacks, especially for color attacks and geometric distortions.

✉ Jianzhong Li
henry_stu@163.com

Chuying Yu
chyyu@hstc.edu.cn

B. B. Gupta
gupta.brij@gmail.com

Xuechang Ren
xuechangren@xmu.edu.cn

1 College of mathematics and statistics, Hanshan Normal University, Chaozhou, China

2 School of physics and electronic engineering, Hanshan Normal University, Chaozhou, China

3 National Institute of Technology Kurukshetra, Kurukshetra, India

4 Department of physics and mechanical & electrical engineering, Xiamen University, Xiamen, China

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1 Introduction

In the last few decades, information security techniques have been receiving considerable attention [2, 14]. With the rapid development of network and multimedia technology [1, 7, 17, 18, 25, 29, 30], to protect the copyright and integrity of digital products has become a great challenge. Therefore, a variety of techniques in the purpose of protecting digital rights have been proposed. Digital watermarking is regarded as one of the most promising techniques to protect digital data among these techniques [5]. In term of the domain in which the watermark is applied, the watermark scheme can be classified into two categories: spatial-domain and frequency-domain methods [6]. In the algorithms of the first group, the watermark is superposed directly on image pixels [10]. On the other hand, the techniques of the second group take advantage of transformation domains, such as discrete Fourier transform (DFT) [16], discrete cosine transform (DCT) [15], discrete wavelet transform (DWT) [6] and singular value decomposition (SVD) [12], for watermarking purpose. In some new researches, Schur decomposition, which requires fewer computations compared to other transforms (e.g. SVD), has been applied in watermarking and proved to be a promising area that may compete with other transform domains [22]. In comparison with spatial domain schemes, the transform domain based watermarking is known as more robust and imperceptibility [6].

In recent years, a large number of image watermarking schemes have been introduced [6, 10, 12, 15, 16, 22]. Though numerous image watermarking schemes have been presented, most of the existing watermarking methods were designed for the copyright protection of grayscale images. However, color images are the basic components of multimedia systems and play an important role in the life now [28]. Hence, it is very important to developed effective watermarking techniques for color images. There exist different color spaces which are the representing models for color images, such as RGB, HSI, YCbCr, HSV and YIQ, could be a candidate to be employed in color image watermarking methods. For protecting the copyright of color image, watermarking schemes reported in [8], [23], [11] and [9] utilize RGB, YCbCr, HIS and YIQ color spaces, respectively. Since these watermarking methods ignore the correlation between different color channels and the significant color information, they are not robust against color attacks [3] including histogram equalization, contrast adjustment, gamma correction, brighten and darken etc., which are implemented easily by using image-editing software.

To overcome the above-mentioned problem, researchers have started to propose models to process the color channels intrinsically. Quaternion, which represents a color image by encoding its three channels on the imaginary parts of quaternion number, offers a solution to achieve this goal and has been employed in color image watermarking [21, 24, 26, 28]. By use of such a representation, a color image can be processed holistically in a vector manner [24]. Tsui et al. developed a non-blind technique that watermark signal is inserted into the quaternion discrete Fourier transform (QDFT) domain of the original color image [26]. Sun et al. proposed that the watermark is embedded into the amplitude of QDFT AC coefficients of the host color image [24]. Shao et al. suggested fusing the encrypted watermark into the middle coefficients of the quaternion gyrator transformed host image [21]. Though these color image watermarking methods consider the correlation between different color components, they cannot resist the geometric attacks, such as rotation and scaling. To withstand geometric attacks, Yang et al. presented a geometric robust color image watermarking approach based on LS-SVM training model and quaternion Exponent moments [28]. The drawbacks of this scheme is the high computation time for LS-SVM training [28].

In this paper, based on quaternion Hadamard transform (QHT) and Schur decomposition, a novel color image watermarking scheme is presented. To process the color image holistically as a vector field, the QHT is defined and its calculation for a color image, which is represented by quaternion matrix, is developed. Then the watermark is embedded into the host color image which is transformed by QHT and Schur decomposition. In the extraction procedure, the quaternion Zernike moment (QZM) [4] is employed to estimate the geometric distortion parameters of the attacked watermarked image. Experimental results show that the proposed scheme is invisible and robust against attacks including contrast adjustment, histogram equalization, gamma correction, brighten, darken, sharpening, filtering, noise addition, occlusion, rotation, scaling and combined geometric attacks, etc.

2 Preliminaries

2.1 Quaternion representation of a color image

Quaternions can be considered as generalizations of complex numbers. A quaternion number can be represented as follows [21]:

$$q = a + bi + cj + dk, \tag{1}$$

where a, b, c, and d are real numbers, and i, j, and k are three imaginary units obeying the following rules

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

The conjugate and modulus of a quaternion are respectively defined by

$$q^* = a - bi - cj - dk, \quad |q| = \sqrt{a^2 + b^2 + c^2 + d^2}. \tag{3}$$

When $a = 0$, q is a pure quaternion. Let f be a color image in the RGB color space. Each image pixel can be treated as a pure quaternion number which real part is 0:

$$f_Q = f_R i + f_G j + f_B k, \tag{4}$$

where f_R, f_G, and f_B are the red, green and blue channels of f, respectively. By employing this representation, each color triple can be treated as a whole unit and be processed directly, without losing color information.

2.2 Hadamard transformation technique

The Hadamard transform (HT) is a non-sinusoidal, orthogonal transformation that decomposes a signal into a set of orthogonal, rectangular waveforms called Walsh functions [20]. Early studies [13, 20] make clear that the use of Hadamard transform as signal decomposition tool can not only offer simple implementation, low computation cost and ease of hardware implementation, but also be suitable for hiding the watermark. HT has two properties: one is that its elements are real; the other is that its rows and columns are orthogonal to each other [20]. Hence, $H = H^* = H^T = H^{-1}$ [20]. Here, H is a Hadamard matrix and H^*, H^T and H^{-1} are the corresponding transpose matrix, inverse matrix and conjugate matrix, respectively. The product of Hadamard matrix H and its transpose H^T is an identity matrix [20].

Let g be the original image and G the transformed image, the two-dimensional (2D) Hadamard transform is defined as [20]

$$G = H_N g H_N / N, \tag{5}$$

where H_N is an $N \times N$ Hadamard matrix.

The inverse 2D–Hadamard transform (IHT) is given as [20]

$$g = H_N^{-1} G H_N^* / N = H_N G H_N / N, \tag{6}$$

2.3 Schur decomposition

In the mathematical discipline of linear algebra, the Schur decomposition is an important tool in matrix decomposition. Since Schur decomposition is a major intermediate step in SVD, it has lower computational complexity than that of SVD [22]. Therefore, Schur decomposition has been suggested to be applied in watermarking domain [19, 22]. The Schur decomposition of a real matrix A results in two matrices Q and S as shown in the following formulas [29]

$$A = QSQ^T, \tag{7}$$

where S is the block upper triangular matrix called the real Schur form and Q is a unitary matrix. Q^T indicates the conjugate transpose of Q.

Note that all the signs of the first column elements in matrix Q are same and their values are very similar [22]. Thus, we utilized this property and insert the watermark into the coefficients in Q matrix of the QHT-transformed component after Schur decomposition.

2.4 Quaternion Zernike moment

By using the algebra of quaternions, Chen et al. introduced the quaternion Zernike moments, which are invariant to rotation, scaling and translation transformations, to process the color images in a holistic manner [28]. Owning to the non-commutative multiplication property of quaternions, two types of QZM, which are the left-side QZM and the right-side QZM respectively, can be defined [28]. In this work, the right-side QZM is used.

Let $f(r,\theta)$ be an RGB image, the right-side QZMs of order n with repetition m is defined as [28]

$$Z^R_{n,m}(f) = \frac{n+1}{\pi} \int_0^1 \int_0^{2\pi} R_{n,m}(r) f(r,\theta) e^{-\mu m\theta} r\mathrm{d}\theta\mathrm{d}r, \tag{8}$$

where $|m| \le n$ and $n-|m|$ is even and $\boldsymbol{\mu}$ is a unit pure quaternion which meets the constraint that $\boldsymbol{\mu}^2 = -1$ and $R_{n,m}(r)$ is the real-valued radial polynomial given by [28]

$$R_{n,m}(r) = \sum_{k=0}^{(n-|m|)/2} \frac{(-1)^k (n-k)!}{k!\Big(((n+|m|)/2-k)!\Big(((n-|m|/2)-k)!} r^{n-2k} \tag{9}$$

3 Quaternion Hadamard transform

3.1 Definition

Because of the non-commutative multiplication property of quaternions, there are different types of QHT that can be defined. In this study, the left-side QHT ($\mathrm{QHT_L}$) and the right-side QHT ($\mathrm{QHT_R}$) are defined:

- Left-side QHT:

$$F_{QL} = QHT_L\left(f_q\right) = \mu H_N f_q H_N / N, \tag{10}$$

- Right-side QHT:

$$F_{QR} = QHT_R\left(f_q\right) = H_N f_q H_N \mu / N, \tag{11}$$

where f_q is a two-dimensional quaternion function. $QHT_L()$ and $QHT_R()$ are the left-side QHT and right-side QHT operations, respectively.

The corresponding inverse QHT (IQHT) are defined as follows

- Left-side IQHT ($\mathrm{IQHT_L}$):

$$f_q^{'} = \mathrm{IQHT}_L\left(F_{QL}\right) = -\mu H_N^{-1} F_{QL} H_N^{*} / N = -\mu H_N F_{QL} H_N / N, \tag{12}$$

- Right-side IQHT ($\mathrm{IQHT_R}$):

$$f_q^{'} = \mathrm{IQHT}_R\left(F_{QR}\right) = -H_N^{-1} F_{QR} H_N^{*} \mu / N = -H_N F_{QR} H_N \mu / N, \tag{13}$$

In formulas (12) and (13), $IQHT_L()$ and $IQHT_R()$ are the inverse left-side QHT and right-side QHT operations, respectively. QHT and IQHT are transformation pairs of each other. They insure that a quaternion function f_q which is transformed into the QHT domain can be reconstructed completely by the inverse process without losing any information. When f_q represents a color image, it can be processed holistically in a vector manner by using QHT.

3.2 Analysis on QHT for color image watermarking

It can be observed from Eq. (4) that the real parts of the quaternion matrix which represents a color image are equal to zero. Hence, the corresponding reconstructed quaternion matrix, which is obtained by employing QHT and IQHT, must be a pure quaternion matrix after watermark embedding. Otherwise, if the real parts of the reconstructed quaternion matrix are not equal to zero, the watermarked color image which is acquired by taking only the three imaginary parts of it (see Eq. (4)) will discard non-zero real part data and bring about a loss of watermark information

For left-side QHT, substituting $\boldsymbol{\mu}$ and Eq. (4) into Eq. (10), we have

$$\begin{aligned} F_{QL} = QHT_L\left(f_Q\right) &= \mu H_N f_Q H_N \Big/ N = \mu\left[H_N(\mathrm{i}f_R + jf_G + kf_B)H_N\right]\Big/ N \\ &= \mu\left[iH_N f_R H_N + jH_N f_G H_N + kH_N f_B H_N\right]\Big/ N \\ &= \mu\left[iHT(f_R) + jHT(f_G) + kHT(f_B)\right] \end{aligned} \tag{14}$$

Considering the general unit pure quaternion $\boldsymbol{\mu} = \alpha i + \beta j + \gamma k$ (α, β and γ are real numbers), substituting $\boldsymbol{\mu}$ into (14) and using the properties of the quaternion shown in Eq. (2), we have

$$F_{QL} = F_0 + \mathrm{i}F_1 + jF_2 + kF_3, \tag{15}$$

where

$$\begin{aligned} &F_0 = -\alpha HT(f_R) - \beta HT(f_G) - \gamma HT(f_B), \qquad F_1 = \beta HT(f_B) - \gamma HT(f_G), \\ &F_2 = \gamma HT(f_R) - \alpha HT(f_B), \qquad F_3 = \alpha HT(f_G) - \beta HT(f_R). \end{aligned} \tag{16}$$

Similarly, applying left-side IQHT to Eq. (12), the reconstructed f'_Q can be obtained.

$$f'_Q = \mathrm{IQHT}_L\left(F_{QL}\right) = \mathrm{IQHT}_L(F_0 + \mathrm{i}F_1 + jF_2 + kF_3) = f'_{re} + \mathrm{i}f'_R + jf'_G + kf'_B, \tag{17}$$

where

$$\begin{aligned} f'_{re} &= \alpha f'_1 + \beta f'_2 + \gamma f'_3, \quad f'_R = \gamma f'_2 - \alpha f'_0 - \beta f'_3, \quad f'_G = \alpha f'_3 - \beta f'_0 - \gamma f'_1, \quad f'_B \\ &= \beta f'_1 - \gamma f'_0 - \alpha f'_2. \end{aligned} \tag{18}$$

where

$$f'_0 = IHT(F_0), \qquad f'_1 = IHT(F_1), \qquad f'_2 = IHT(F_2), \qquad f'_3 = IHT(F_3). \tag{19}$$

It can be seen from Eqs. (14)–(19), by use of the traditional HT and IHT algorithms, the left-side QHT and IQHT of a color image which is represented by quaternion algebra can be calculated effectively. Notice that the right-side QHT of a color image can be implemented in a similar way. As mentioned before, to represent a color image, f'_Q must be a pure quaternion matrix. Therefore, the real parts of f'_Q are equal to zero. That is $f'_{re} = 0$. It can be observed from Eq. (18), f'_{re} is computed without using f'_0, while the three imaginary parts of f'_Q are calculated by utilizing f'_0. It can be concluded that $f'_{re} = 0$ can be still satisfied even if f'_0 has been modified (e.g. watermark embedding). Since f'_R, f'_G and f'_B are employed to reconstruct the color image, the changes of f'_0 will be spread to these three channels simultaneously. Consequently, when the watermark is inserted into f'_0, not only the loss of watermark information can be avoided, but also the correlation between different color channels is considered. In this study, f'_0 is chosen to embed the watermark.

By use of QHT, the advantage of processing a color image in a holistic manner without separating it into three channels can be obtained. The successful application in color image watermarking by use of the QHT which will be described in the following section shows its great potential. And we'd like to point out that, besides color image watermarking, the proposed QHT can be used for other color image processing fields, such as image template matching and image enhancement.

4 Rotation and scaling distortion parameters detection based on quaternion Zernike moment

To extract the watermark accurately, the rotation and scaling transform parameters of watermarked color image are estimated based on QZMs, and then correct the distorted watermarked color image by using these estimated parameters for the geometric attacks including rotation, scaling and combined rotation and scaling transformations.

4.1 Rotation detection

If a color image is rotated by θ degrees, the relationship between the original color image and the rotated color image is [4]

$$Z'^{R}_{n,m} = Z^{R}_{n,m} e^{-\mu m\theta}. \tag{20}$$

where $Z'^{R}_{n,m}$ and $Z^{R}_{n,m}$ are the right-side QZM of the original and the rotated image respectively. The rotated angle θ can be estimated by using the following formula

$$\theta = -\frac{\arg\left(Z'^{R}_{n,m}\right) - \arg\left(Z^{R}_{n,m}\right)}{m}, \quad (m \neq 0). \tag{21}$$

Here, *arg*() denotes the phase extraction operator. The rotation parameter θ can also be estimated by employing the left-side QZM in a similar way.

4.2 Scaling detection

Assume that *f*" denotes a scaled version (with the scaling factor λ) of the original color image *f*. Let $\Gamma_f = \left(|Z^{R}_{0,0}|\right)^{1/2}$. Based on the definition of Γ_f, it can be verified that [4]

$$\Gamma_{f'} = \lambda \Gamma_f. \tag{22}$$

Then the scaling factor can be figured out as follows

$$\lambda = \Gamma_{f'} / \Gamma_f = \sqrt{\left|Z'^{R}_{0,0}\right| / \left|Z^{R}_{0,0}\right|}. \tag{23}$$

Using the two detection methods mentioned above, the geometric distortion parameters of a color image which is under the combined rotation and scaling attacks can also be estimated.

In addition, the original color image is not needed for the above-mentioned detection procedures. However, some information of the original image including the right-side QZMs $Z^{R}_{0,0}$, $Z^{R}_{1,1}$ and $Z^{R}_{2,2}$ is required. Since the color image is processed in a holistic manner via

QZM, the correlation between different color channels and the significant color information is considered in the detection method. As a result, it is robust to the chromatic distortions such as brightness modifications.

5 The proposed watermarking method

A color image watermarking scheme, including its watermark embedding and extraction processes is proposed in this section. As mentioned above, QHT has the ability to distribute watermark energy to three channels simultaneously. Using the QZMs of color image, we can obtain an accurate estimation of geometric transformation parameters to make our scheme robust to geometric attacks.

5.1 Watermark embedding algorithm

The binary watermark is embedded into the host color image which is transformed by QHT and Schur decomposition. Let H and W be the color host image and the original watermark image, respectively. The watermarking process is described as follows.

1) To deal with the host color image in a holistic manner, H is transformed by QHT using Eqs. (14) and (15) to achieve F_{QL} first. Then apply IQHT to F_{QL} to acquire f'_Q by employing Eq. (17). According to the analysis mentioned in sub-section 3.2, the component f'_0 is chosen to embed the watermark.
2) Divide f'_0 into non-overlapping blocks with 8 × 8 pixels. Let $f_{mn}'_0$ be the $(m,n)^{\text{th}}$ block in f'_0.
3) Apply Schur decomposition to every block $f_{mn}'_0$ to get Q_{mn} and S_{mn}: $f_{mn}'_0 = Q_{mn}S_{mn}Q_{mn}^T$.
4) An element of the W is embedded into one block in the embedding procedure. Each Q_{mn} matrix of the to-be-embedded block is altered to insert the watermark. Let W_{mn} be the $(m,n)^{\text{th}}$ element of W. The watermark is inserted by using the following formulas.

$$\text{if}\quad W_{mn}=1,\begin{cases} q'_{mn3,1}=\text{sign}\left(q_{mn3,1}\right)\times(1+\Delta)avg \\ q'_{mn2,1}=\text{sign}\left(q_{mn2,1}\right)\times\left[abs\left(q_{mn2,1}\right)-\Delta avg/2\right] \\ q'_{mn4,1}=\text{sign}\left(q_{mn4,1}\right)\times\left[abs\left(q_{mn4,1}\right)-\Delta avg/2\right] \end{cases}\tag{24}$$

$$\text{if}\quad W_{mn}=0,\begin{cases} q'_{mn3,1}=\text{sign}\left(q_{mn3,1}\right)\times(1-\Delta)avg \\ q'_{mn2,1}=\text{sign}\left(q_{mn2,1}\right)\times\left[abs\left(q_{mn2,1}\right)+\Delta avg/2\right] \\ q'_{mn4,1}=\text{sign}\left(q_{mn4,1}\right)\times\left[abs\left(q_{mn4,1}\right)+\Delta avg/2\right] \end{cases}\tag{25}$$

where $q_{mn2,1}$, $q_{mn3,1}$ and $q_{mn4,1}$ are the second, the third and the fourth elements in the first column of Q_{mn}, respectively. $Avg.=(|q_{mn2,1}|+|q_{mn4,1}|)/2$ and Δ is the embedding control factor. $Sign(x)$ denotes the sign of x and $abs(x)$ returns the absolute value of x, respectively. Let

Q'_{mn} denote the altered Q_{mn}. Experimental results indicate that the proposed method has good invisibility and robustness when Δ is between 0.02 and 0.04.

1) Use the following formula to acquire the watermarked component f''_0

$$f_{mn}{}''_0 = Q'_{mn} S_{mn} Q'^{T}_{mn}, \tag{26}$$

where $f_{mn}{}''_0$ be the $(m,n)^{th}$ block in f''_0.

2) Using Eq. (18), calculate the three components f'_R, f'_G and f'_B with f''_0 to spread watermark energy into three imaginary parts of f'_Q. Let f''_R, f''_G and f''_B be the three watermarked imaginary components after calculation, respectively.
3) Compose the three channels f''_R, f''_G and f''_B, the watermarked color image can be generated.
4) Calculate the QZMs $Z^R_{0,0}$, $Z^R_{1,1}$ and $Z^R_{2,2}$ of the watermarked color image, which are needed in the detection process.

5.2 Watermark extraction

The watermark can be extracted without the host color image, but quaternion Zemike moments obtained in step 8) of the watermark embedding procedure are needed to estimate the geometric transformation parameters.

1) Let *WI* denote the watermarked color image. Using the method described in section 4, *WI* is inspected for geometric attacks including rotation, scaling and combine attack sequentially. If a possible attack (e.g., scaling) is detected successfully, the detection procedure is terminated and *WI* is corrected by use of the estimated geometric transformation parameters. Let *WI* indicate the recovered color image.
2) Apply QHT to *WI* to get FW_{QL} first. Then transform FW_{QL} by IQHT to obtain fw'_Q. Then the component fw'_0, which is corresponding to f'_0 in embedding procedure, is employed to extract the watermark.
3) Divide fw'_0 is into non-overlapping blocks with 8 × 8 pixels. Let $fw_{mn}{}'_0$ denote the $(m,n)^{th}$ block in fw'_0.
4) Perform Schur decomposition on every block to obtain the Q component. Let Qw_{mn} denote the corresponding Q matrix of $fw_{mn}{}'_0$.
5) The watermark W' is extracted according to the following formula.

$$W'_{mn} = \begin{cases} 1, & \text{if } \left|qw_{mn3,1}\right| > \text{avgw} \\ 0, & \text{if } \left|qw_{mn3,1}\right| \le \text{avgw} \end{cases}, \tag{27}$$

where $avgw = (|qw_{mn2,1}| + |qw_{mn4,1}|)/2$. $qw_{mn2,1}$, $qw_{mn3,1}$ and $qw_{mn4,1}$ are the second, the third and the fourth elements in the first column of Qw_{mn}, respectively.

6 Experimental results

The performance, including imperceptibility and robustness, of the proposed scheme are verified by watermarking the original color images. The structural similarity (SSIM) index [23, 27], which was considered to be correlated with the quality perception of the human visual system (HVS), was used to evaluate the similarity between the original color image H and the watermarked color image H''. Different from conventional error summation methods, e.g. PSNR, the SSIM is developed via modeling any image distortion as a combination of the luminance distortion, the contrast distortion and loss of correlation [27]. The SSIM is defined as [23, 27]:

$$\mathrm{SSIM}(H,H') = \left(\frac{2\mu_H\mu_{H'} + C1}{\mu_H^2 + \mu_{H'}^2 + C1}\right)\left(\frac{2\sigma_H\sigma_{H'} + C2}{\sigma_H^2 + \sigma_{H'}^2 + C2}\right)\left(\frac{\sigma_{HH'} + C3}{\sigma_H\sigma_{H'} + C3}\right), \quad (28)$$

where μ_H and $\mu_{H'}$ are the two images' mean luminance, σ_H and $\sigma_{H'}$ are the standard deviations for the two images, and $\sigma_{HH'}$ is the covariance between H and H', respectively. The positive constants C_1, C_2 and C_3 are used to avoid a null denominator. The values of the SSIM are in [0, 1]. The higher the SSIM is, the better the image quality is. To measure the correctness of the extracted watermark, the normalized correlation (NC) [23] between the embedded watermark $W(m,n)$ and the extracted watermark $W'(m,n)$ was used as a similarity metric.

$$NC = \sum_{m=1}^{M}\sum_{n=1}^{N}\left[W(m,n) \times W'(m,n)\right] \Big/ \sum_{m=1}^{M}\sum_{n=1}^{N}\left[W^2(m,n)\right]. \quad (29)$$

The sizes of the both watermarks are $M \times N$. The NC is a metric to determine the robustness of extracted watermark from the attacked image. From Eq. (29), $NC \in [0, 1]$. In general, NC about 0.7 or above is considered acceptable.

The standard test color images including Lena, Peppers and Baboon (512 × 512 × 24) and a binary logo rose (64 × 64 × 2), which are shown in Fig. 1, were adopted as the host images and the watermark. In the Experiments, the unit pure quaternion is $\boldsymbol{\mu} = (i + j + k)/3^{1/2}$, and $\Delta = 0.03$. The simulations in the experiment were implemented using MATLAB.

Fig. 2 shows the results of the proposed watermarking method without any attacks. In Fig.2, (a), (c) and (e) are the watermarked color images, (b), (d) and (f) depict the watermarks which were extracted from the corresponding watermarked images. The SSIM values of the watermarked color images, which are compared with the scheme in [23], are listed in Table 1. It can be observed from Fig.2 and Table 1 that the watermarked color images whose SSIM values are approximately 1 have good imperceptibility and almost have no difference from the original ones in visual quality.

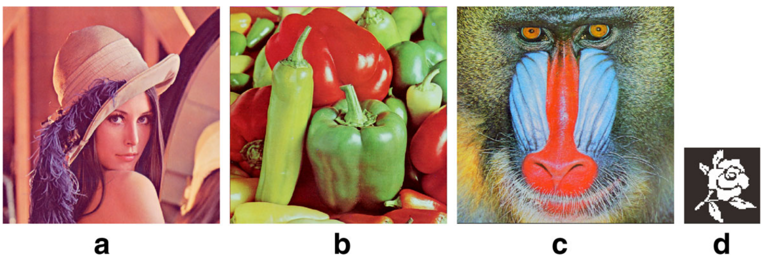

Fig. 1 The host color images and the binary watermark. **a** Lena; **b** Peppers; **c** Baboon; **d** rose

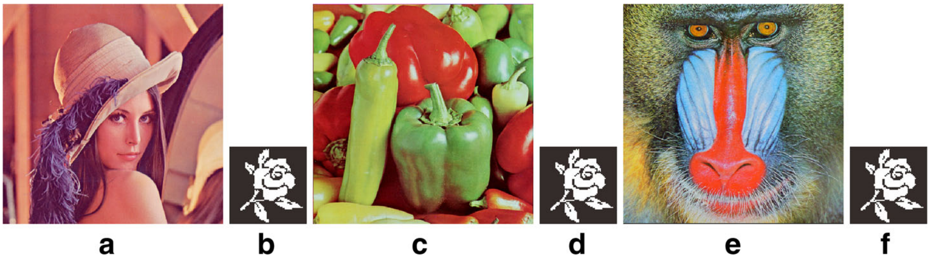

Fig. 2 The watermarked images and the corresponding extracted watermark without any attacks. **a** The watermarked "Lena". **b** extracted watermark of (a) (NC = 1). **c** the watermarked "Peppers". (d) extracted watermark (NC = 1). (e) the watermarked "Baboon". (f) extracted watermark of (e) (NC = 1)

To investigate the robustness of the proposed schemes, various attacks have been applied on the watermarked images, including contrast adjustment, histogram equalization, gamma correction, brighten, darken, sharpening, noise addition, filtering, cropping, JPEG compression, rotation, scaling and combined geometric attacks. Fig. 3 shows some attacked watermarked images. The corresponding watermarks which are extracted from the above attacked images in Fig. 4. The *SSIMs* of the corrupted watermarked images are also presented in Fig. 3. In Fig. 3, the 'N/A' indicates that the *SSIM* can not be calculate because the size of the distorted image is not the same as that of the original watermarked image. For all attack cases, the NC values obtained from both proposed method and scheme in [23] are presented in Table 2. In Table 2, the ' /[a]' and ' /[b]' indicate that Su's method cannot withstand the corresponding attack [23] and the experimental result is not provided in the literature [23], respectively. It can be observed from the Table 2 and Fig. 4 that, although the watermarked images suffer from serious distortion, the presented scheme the proposed scheme offers satisfactory results for most attacks. All the extracted watermarks are clear enough to be recognized and most of the corresponding NC values are larger than 0.8.

It can be seen from Table 2 that, although the method in [23] achieves good results, i.e., filtering operation and noise addition, it fails to resist color attacks including histogram equalization, contrast adjustment, gamma correction, brighten and darken. The proposed method have large NC values in the case of the mentioned above color attacks since it employs a holistically processing approach by use of QHT. That is, our scheme is robust against color attacks.

Though Su et al. claimed that the method in [23] is robust against geometric attacks, it cannot resist the geometric attacks effectively. That reason is that it is assumed that the transformation parameters of the geometric distorted watermarked color images have been known and used for correcting geometric distorted watermarked images before watermark extraction. However, without using any estimation algorithm, it is hardly to obtain the geometric transformation parameters. As can be seen from the Table 2 and Fig. 4, our method

Table 1 SSIM Values of watermarked color images between proposed method and scheme in [23]

Algorithm	Lena	Peppers	Baboon
Propose method	0.9917	0.9892	0.9883
Scheme in [23]	0.9869	0.9856	0.9956

Fig. 3 The attacked watermarked images under attacks. **a** contrast adjustment (*SSIM* = 0.7283); **b** histogram equalization (*SSIM* = 0.6642); **c** gamma correction (*SSIM* = 0.8541); **d** brighten (*SSIM* = 0.7639); **e** darken (*SSIM* = 0.5327); **f** sharpening (*SSIM* = 0.5650); **g** Gaussian low-pass filtering (*SSIM* = 0.8931); **h** Butterworth high-pass filtering (*SSIM* = 0.8428); **i** median filtering (*SSIM* = 0.7234); **j** salt & pepper noise (*SSIM* = 0.7648); **k** Gaussian noise (*SSIM* = 0.3858); **l** cropping (*SSIM* = 0.7474); **m** JPEG (*SSIM* = 0.9884); **n** rotation (*SSIM* = 0.8187); **o** scaling (*SSIM* = N/A); **p** rotation + scaling (*SSIM* = N/A)

is robust to geometric attacks including rotation, scaling and a combination of them effectively because the parameters of these geometric transformations can be estimated exactly by use of the QZM-based geometric detection algorithm described in section 4. In the experiments, all the watermarked color images were rotated with 10°, scaled with factor 1.6 and transformed by a combination of rotation 20° and scaling 1.5, respectively. The corresponding estimated distortion parameters of Fig. (n), Fig. (o) and Fig. (p) are 10.0227°, 1.603 and 20.035° and 1.506, respectively. After correcting the geometric distorted watermarked color images by use of these parameters, the watermarks can be extracted. All the watermarks can be distinguished and the NC values of them are greater than 0.8. From the above experiments, it appears that our algorithm can resist geometric attacks including rotation, scaling and combined rotation and scaling.

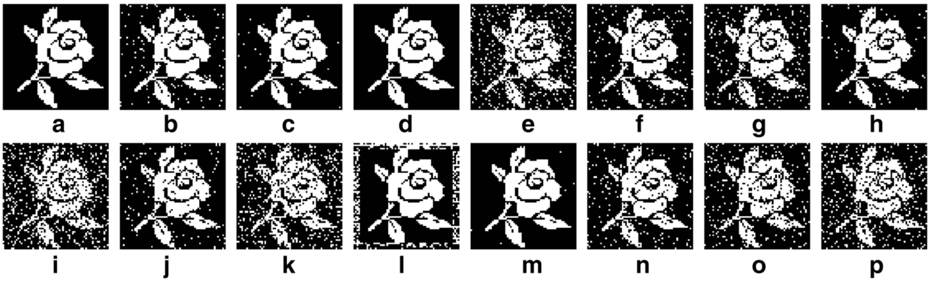

Fig. 4 The corresponding extracted watermarks from the distorted watermarked images in Fig. 3. **a** contrast adjustment; **b** histogram equalization; **c** gamma correction; **d** brighten; **e** darken; **f** sharpening; **g** Gaussian low-pass filtering; **h** Butterworth high-pass filtering; **i** median filtering; **j** salt & pepper noise; **k** Gaussian noise; **l** cropping; **m** JPEG; **n** rotation; **o** scaling; **p** rotation + scaling

From the above measurements, several observations can be achieved. The proposed color image watermarking method offers satisfactory results for most attacks, especially for color attacks and geometric distortions. However, it is not very robust against some attacks, such as translation, median filtering and JEPG compression. The reasons are: (1) the QZM-based geometric distortion detection algorithm cannot measure the translation parameters effectively due to the lost information of the translated image; (2) some attacks such as median filtering and JEPG compression can destroy significantly the coefficients of the component of the host color image after QHT and Schur decomposition.

Table 2 NC values of extracted watermarks under attacks comparing between proposed method and scheme in [23]

Attack Type	Lena		Peppers		Baboon	
	Proposed method	Scheme in [23]	Proposed method	Scheme in [23]	Proposed method	Scheme in [23]
No attack	1	1	1	0.9930	1	1
Contrast adjustment	0.9991	/[a]	0.9662	/[a]	0.9459	/[a]
Histogram equalization	0.9991	/[a]	0.9865	/[a]	0.9802	/[a]
Gamma correction	1	/[a]	0.9937	/[a]	0.9901	/[a]
Brighten (add 90 to each pixel)	1	/[a]	0.9964	/[a]	0.9955	/[a]
Darken (subtract 60 from each pixel)	0.9153	/[a]	0.8739	/[a]	0.8874	/[a]
Sharpening	0.9991	/[b]	0.9874	/[b]	0.9532	/[b]
Gaussian low-pass filtering (hsize =3, sigma =0.9)	0.9243	/[b]	0.8613	/[b]	0.8441	/[b]
Butterworth high-pass filtering	0.9973	/[b]	0.9667	/[b]	0.9802	/[b]
Median filtering	0.8811	0.9674	0.8162	0.9683	0.7647	0.9965
Salt & pepper noise	0.9396	0.9378	0.9228	0.9257	0.9450	0.9413
Gaussian noise	0.9063	0.9670	0.8541	0.9543	0.8883	0.9633
Cropping (20%)	0.9910	0.9846	0.9847	0.9820	0.9865	0.9901
JPEG (90%)	0.9955	0.9985	0.9604	0.9885	0.9775	0.9980
Rotation (10°)	0.9596	/[a]	0.9491	/[a]	0.9333	/[a]
Scaling (1.6)	0.9640	/[a]	0.9258	/[a]	0.8964	/[a]
Rotation (20°) + scaling(1.5)	0.8667	/[a]	0.8604	/[a]	0.7854	/[a]

"/[a] " indicate that it cannot resist this attack

"/[b] " indicate that the result is not provided

7 Conclusion

In this paper, the conventional Hadamard transform defined in gray-scale image is extended to color image using the algebra of quaternions first. Then an efficient method to calculate the QHT of a quaternion matrix is developed. Based on QHT and Schur decomposition, a novel color image watermarking scheme is presented. With QHT, the host color image is processed in a holistic manner and the watermark is embedded by changing the elements of Q matrix obtained by Schur decomposition. In order to withstand the geometric attacks, a geometric distortion detection algorithm based upon QZM, which considers the significant color information, is introduced. Before extracting the watermark, the geometric transformation parameters of corrupted watermarked image is estimated by using this algorithm. Subsequently, the distorted color image is corrected by employing the estimated distortion parameters, and the watermark can be extracted from the recovered image. Experimental results show that the proposed scheme not only has good imperceptibility but also is robust to various kinds of attacks, including contrast adjustment, histogram equalization, gamma correction, brighten, darken, sharpening, filtering, noise addition, cropping, rotation, scaling and combined geometric attacks, etc. In sum, compared with the earlier color image watermarking schemes in the literature, the advantages of the proposed approach are: (1) the robustness against color attacks is higher because the watermark is spread throughout the three RGB channels rather than simply considering the image luminance component; (2) since the rotation and scaling transform parameters of geometric distorted watermarked color image can be estimated by QZMs, the robustness against geometrical distortions is higher; (3) the complexity of it is lower than that of three channels separately processing method. Additionally, in the future work, we will extend the proposed idea to color video watermarking since color images are the basic component of video technologies.

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Jianzhong Li received the Master degree in Computer Science from Shantou University in 2005, and the Ph.D. degree in Optics from the Xiamen University, China, in 2011. He is now an associate professor of the college of mathematics and statistics of Hanshan Normal University, China. His research interests include information security and image processing.

Chuying Yu received the Master degree in Computer Science from Guangdong University of Technology, China, in 2012. She is now an associate professor of the school of physics and electronic engineering of Hanshan Normal University, China. Her research interests include information security and embedded system.

Dr. B.B. Gupta received PhD degree from Indian Institute of Technology Roorkee, India in the area of Information and Cyber Security. In 2009, he was selected for Canadian Commonwealth Scholarship and awarded by Government of Canada Award ($10,000). He spent more than six months in University of Saskatchewan (UofS), Canada to complete a portion of his research work. He has published more than 70 research papers (including 01 book and 08 chapters) in International Journals and Conferences of high repute including IEEE, Elsevier, ACM, Springer, Wiley Inderscience, etc. He has visited several countries, i.e. Canada, Japan, China, Malaysia, Hong-Kong, etc. to present his research work. His biography was selected and publishes in the 30th Edition of Marquis Who's Who in the World, 2012. He is also working principal investigator of various R&D projects. He is also serving as reviewer for Journals of IEEE, Springer, Wiley, Taylor & Francis, etc. He is serving as guest editor of various Journals. He was also visiting researcher with Yamaguchi University, Japan in 2015 and with Guangzhou University, China in 2016, respectively. At present, Dr. Gupta is working as Assistant Professor in the Department of Computer Engineering, National Institute of Technology Kurukshetra, India. His research interest includes Information security, Cyber Security, Mobile/Smartphone, Cloud Computing, Web security, Intrusion detection, Computer networks and Phishing.

Xuechang Ren received the B.S. degree in Radio Physics from Xiamen University in 1999, and the Ph.D. degree in Condensed Matter Physics from Xiamen University, China, in 2004. She is now an associate professor of College of Physical Science and Technology of Xiamen University, China. Her research interests include Optical imaging, displaying technology and image processing.