An efficient and self-adapting colour-image encryption algorithm based on chaos and interactions among multiple layers

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Abstract In this paper, we propose an efficient and self-adapting colour-image encryption algorithm based on chaos and the interactions among multiple red, green and blue (RGB) layers. Our study uses two chaotic systems and the interactions among the multiple layers to strengthen the cryptosystem for the colour-image encryption, which can achieve better confusion and diffusion performances. In the confusion process, we use the novel Rubik's Cube Scheme (RCS) to scramble the image. The significant advantage of this approach is that it sufficiently destroys the correlation among the different layers of colour image, which is the most important feature of the randomness for the encryption. The theoretical analysis and experimental results show that the proposed algorithm can improve the encoding efficiency, enhances the security of the cipher-text, has a large key space and high key sensitivity, and is also able to resist statistical and exhaustive attacks.

Keywords Colour-image encryption · Chaos · Interaction of multiple layers · Security analysis

1 Introduction

The security of multimedia data has become increasingly important due to the advances in networking technology coupled with the popularity of the internet [15]. Therefore, designing an effective and fast encryption method to ensure the safety of image data in a variety of communication network transmissions has received widespread attention [7]. However,

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traditional image encryption schemes, e.g. Data Encryption Standard (DES) [32], Advanced Encryption Standard (AES) [10], and Rivest Shamir Adleman (RSA) et al. [6], (in which the image is represented as a plaintext for encryption), are not suitable for image encryption due to the special features of images, e.g. bulky data capacity, strong redundancy and high correlations between adjacent pixels [6]. Chaotic systems have many important properties, such as sensitive dependence on initial conditions and parameters, unpredictability, similar randomness, aperiodicity and ergodicity, which make chaotic systems popular in image encryption [22, 23]. In the past 20 years, a large number of chaos-based encryption schemes have been designed [12, 16, 50]. According to the Shannon information theory, confusion and diffusion are two properties of the operation of a secure cipher in cryptography [27, 45, 46]. Specifically, confusion means that each binary digit/bit of the cipher-text should depend on several parts of the key, obscuring the connections between the two, and diffusion is that if a single bit of the plain-text is changed, then half of the bits in the cipher-text should be statistically changed, and similarly, if a one bit of the cipher-text is changed, then half of the bits in the plain-text should be statistically changed. Through much research and analysis [4, 8, 34], we have discovered that both confusion and diffusion are simultaneously employed in one image encryption scheme, resulting in substantial performance improvements.

However, by comparing the encryption performances of many confusion-diffusion schemes, it was found that most of them contain security defects [3, 26, 28]. For instance for the colour-image encryption schemes proposed in recent years [20, 25, 27, 33, 37, 41, 47], most of them used the same method to encrypt the red, green and blue layers [20]. They neglect the correlations among these layers and are more vulnerable to attacks. To overcome this problem, Wang et al. [36] presented a novel colour-image encryption algorithm based on the chaotic logistic map. The main advantage of this algorithm is the simultaneous encryption of the different layers of a colour image, taking into consideration their correlations. By using this algorithm, the correlation among the components is reduced, but the proposed algorithm also has some disadvantages: the key space is defined over periodic orbits of the chaotic map, which reduces the size of the space key; it uses data directly from the logistic map, which affects the encryption properties; and the security analyses of information entropy and time encryption are not included. The Wang algorithm [36] was efficiently cryptanalysed by a plain-image attack by Li et al. in the approach [18]. In addition in the approach [25], researchers proposed an RGB image encryption algorithm based on total plain-image characteristics and chaos, where the initial parameters of the chaotic system are gained through the plain-image pixel operations of summation and remainder. The advantages of this scheme are its simplicity and ease of design, but the disadvantage is obvious too. Using only the simple summation and remainder operations, it is difficult to reflect the main characteristics of the plain image. Luo et al. [23] used the quantification results for plain-image information and the external secret keys as the initial values of the chaotic system, to ensure that the initial parameters of the chaotic system are strict to plain image. High speed and plaintext sensitivity are the main advantages of this research, but the shortcoming is that the permutation result isn't ideal. This is because they construct the pseudo-random sequence using an unbalanced method, which leads to a poor randomness of the ergodic matrix. Then, Wang et al. proposed a new image encryption scheme [42], which used the simulated annealing algorithm to generate the random sequence for the confusion phase. The merit of this scheme is that the random sequence is generated excellently, but there is an obvious problem that some plain-image pixels still remain at their original positions after permutation. Several image encryption schemes based on cat map are presented [1, 6, 14, 17, 27, 48], such as 1-D cat map [1, 6, 27], 2-D cat map and 3-D

cat map [14, 17, 48]. The main advantage of using the cat map is high computing speed. However, different types of cat maps suffer from some common problems. For example, a novel 3-D cat map-based spatial bit-level permutation strategy is proposed by Chen et al. [9]. This scheme cannot resist differential cryptanalysis, according to the analysis by Wang et al. [35]. In addition, the cat map is limited by the size of the plain image, the key space is also not large enough, and the secret key stays the same for different images [21]. Therefore, achieving self-adaption using the cat map is difficult which also lacks of universality.

According to the aforementioned analysis, it is clear that the previous approaches focused on improving the security and speed of the algorithm. Based on the comparison in the approaches [20, 25, 27, 33, 37, 41, 47], a good colour-image encryption scheme not only should encrypt the layers with different methods to reduce the correlations, but also the initial parameter of the chaotic system should be sensitive to plain images to resist plain-image attacks. The permutation algorithm should be designed reasonably, to achieve a good randomness performance [6, 14, 17, 23, 42, 48]. In addition, according to the approaches [9, 36], a good algorithm should be universal for image encryption applications and have a large key space to resist differential cryptanalysis.

In this paper, we aim to design an efficient and self-adapting colour-image encryption algorithm based on chaos and interactions among multiple layers. We design a complex and effective quantification to improve the security of the cryptosystem. The multiple layers are inter-encrypted to reduce the correlations. Moreover, there are no shape or size limitations for the image. In addition, it can be made suitable for grey-image encryption with small changes. The main contributions of this paper are as follows. (1) A novel decimal quantification method based on the plain image is designed. (2) A novel permutation scheme, based on the Rubik's Cube Scheme (RCS), is constructed. (3) A new customized confusion-diffusion approach is designed. (4) The security analysis of the proposed image encryption scheme is presented in detail.

The rest of this paper is organized as follows. Section 2 describes the preliminary knowledge of the decimal quantification process and two chaotic maps. A novel RCS process is designed through the pixel cycle-shifts and image layer rotation. Section 3 presents the structure of the proposed cryptosystem, which includes the encryption and decryption processes. Section 4 analyses the security performance of the proposed cryptosystem. Section 5 gives a conclusion and discusses future work.

2 Preliminaries

In this section, we mainly introduce the decimal quantification process based on the plain image, two chaotic maps, and the process of the novel Rubik's Cube Scheme.

2.1 The decimal quantification process

In order to make the initial parameters be strict to plain-image information, we design a novel quantification method to obtain a decimal between (0, 1). Then, this decimal is used as the initial value or control parameter of the tent map to ensure that the generated chaotic sequence is strictly related to the pixel layers of the plain-image. Therefore, the performance of the image encryption can be improved significantly due to the close relationship between the plain image and the chaotic system. As shown in Fig. 1, the unidirectional quantification process consists of the following steps.

Step 1. The grey value $I(i, j)$ of each pixel in the original image is firstly mapped to the range of (0, 360) in terms of the Eq. (1), which is denoted as $I1(i, j)$.

$$I1(i, j) = I(i, j) \times 360/255 \quad (1)$$

Step 2. Transform the $I1(i, j)$ to the real numbers $I2(i, j)$ in the range of (-1, 1) in the accordance of the Eq. (2) by using the cosine function.

$$I2(i, j) = \cos(I1(i, j)) \quad (2)$$

Step 3. Set two parameters p and q , and set their initial values are $p=0$ and $q=0$. Then calculate the values of p and q based on $I2(i, j)$ in the terms of Eq. (3).

$$\begin{cases} p = p + \left(\frac{I2(i, j)}{\pi} \times 10^{14} \bmod 1 \right); I2(i, j) \geq 0 \\ q = q + \left(\frac{I2(i, j)}{\pi} \times 10^{14} \bmod -1 \right); I2(i, j) < 0 \end{cases} \quad (3)$$

Step 4. Limit the values of p and q in the range of (-1,1) by using the Eq. (4).

$$\begin{cases} p = p \bmod 1; & p \geq 1 \\ q = q \bmod -1; & q \leq -1 \end{cases} \quad (4)$$

Step 5. Cycle the above process until the last pixel is processed, and get the last decimals p and q .

Fig. 1 The flow chart of the quantification process

As shown above, especially in **Step 3**, it can be seen that the parameters of $\mathbf{p}$ and $\mathbf{q}$ are strictly related to the plain-image information, so it can enhance the performance of the image encryption. Specifically, the process described above can be separately applied to each of the three layers of the colour image. Therefore, we can further obtain three pairs of decimal values for $\mathbf{p}$ and $\mathbf{q}$. Then a decimal $\mathbf{k}$ can be obtained according to the Eq. (5), which will be applied to be the influence factor of the parameter η of the PWLCM chaotic system in the following algorithm.

$$\mathbf{k} = |(\mathbf{p}_R - \mathbf{p}_G + \mathbf{p}_B) - (\mathbf{q}_R - \mathbf{q}_G + \mathbf{q}_B)| \bmod 1 \quad (5)$$

Specifically, in order to make the control parameter η of the PWLCM chaotic system in section 2.2 (b) be in the range of $(0, 0.5)$, the $\mathbf{k}$ cannot equal to 0 because once $\mathbf{k}$ is 0, the control parameter η of the PWLCM would be 0 in the terms of the following Eq. (14). Therefore, If the parameter $\mathbf{k}$ equals to 0 in the Eq. (5), the parameter $\mathbf{k}$ will be reset to be 0.19920307, which makes the initial values and control parameters of the chaotic system unpredictable and improves the security of the encryption system effectively.

2.2 The chaotic maps

(a). The skew tent map is given by

$$x(i) = \begin{cases} x(i-1)/a, & 0 \leq x(i-1) < a, \\ (1-x(i-1))/(1-a), & a \leq x(i-1) \leq 1, \end{cases} \quad (6)$$

where a is the controlling parameter and $a \neq 0.5$. This map has high pseudo-randomness when a is in the interval $(0, 1)$. The skew tent map is widely used in cryptosystems due to the even distribution and high ergodicity [23].

To obtain chaotic sequences to improve the security of permutation for images, each state value of the tent map should be quantified to obtain ideal chaotic sequences by Eq. (7), where w is an integer.

$$x'(i) = x(i) \times 10^{14} \bmod w + 1, \quad i \in (1, w) \quad (7)$$

(b). The PWLCM map is given by

$$x(i+1) = F(x(i), \eta) = \begin{cases} \frac{x(i)}{\eta}, & 0 < x_i < \eta \\ \frac{x(i)-\eta}{2-\eta}, & \eta \leq x_i < 0.5 \\ F(1-x(i), \eta), & 0.5 \leq x_i < 1 \end{cases} \quad (8)$$

where $x(i) \in (0, 1)$. When control parameter $\eta \in (0, 0.5)$, it evolves into a chaotic state, and η can serve as a secret key. The PWLCM system has uniform invariant distribution and very good ergodicity, confusion and determinacy [31], thus it can provide an excellent random sequence that is suitable for the cryptosystem.

2.3 The process of the novel Rubik's Cube Scheme

To illustrate this strategy properly, a colour image of size $M \times N \times 3$ (including the red, green and blue layers) is used for simplicity. Figure 2 is a diagram of the permutation process, and the detailed process is described below.

The cycle-shift and rotation operations for the red, green and blue pixel levels are different. The rows number of the image matrix at any processing stage is L . The scrambling process of the red layer of the image is as follows.

Step 1. Obtain three ergodic sequences in accordance with Eq. (6) and Eq. (7); they are denoted by $x'_R(n)$, $x'_G(n)$ and $x'_B(n)$. Specifically, the three initial values $x_R(1)$, $x_G(1)$ and $x_B(1)$ of the skew tent map are produced by the characteristic values of the different colour layers of the plain image. For example, they can be obtained in two ways: 1) Calculate the percentage of "1" in each bit-plane matrix of plain-image. 2) Use the decimal quantification scheme in Section 2.1. And the number of iterations of the tent map is w ($w = \max(M, N)$).

Fig. 2 The flowchart of the Rubik's cube permutation technology

Step 2. Set $i = 1$, and the j th ($j \in \text{even} \& j \leq \frac{L}{2}$ or $j \in \text{odd} \& j \geq \frac{L}{2}$) row of the red layer matrix is cycle-shifted to the left $x'_G(i)$ times. Therefore, the other rows are cycle-shifted to the right $x'_B(i)$ times, as shown in Eq. (9), where i denotes the i th integer of the sequence and j denotes the j th row of the R-layer matrix.

$$\begin{cases} I_R(j, :, 1) = \text{cycleleft}(I_R(j, :, 1), x'_G(i)); & \text{when } j \in \text{even} \& j \leq \frac{L}{2} \text{ or } j \in \text{odd} \& j \geq \frac{L}{2}; \\ I_R(j, :, 1) = \text{cycright}(I_R(j, :, 1), x'_B(i)); & \text{otherwise;} \end{cases} \quad (9)$$

Step 3. Rotate the generated red layer matrix by 90 degree to the right.

Step 4. Let $i = i + 1$, and continue to cycle-shift and rotate the red layer matrix of the image according to **Step 2** and **Step 3**.

Step 5. When $i > w$, the scrambling operation of the red layer is complete.

Similarly, the permutation processes of the green and blue layers of the image are almost the same, but there are some small differences.

(a). The direction of the cycle-shifted for the green layer is opposite that for the red layer. Specifically, the j th ($j \in \text{odd} \& j \leq \frac{L}{2}$ or $j \in \text{even} \& j \geq \frac{L}{2}$) row of the green layer matrix is cycle-shifted to the left $x'_R(i)$ times, and the others are cycle-shifted to the right $x'_B(i)$ times, as shown in Eq. (10).

$$\begin{cases} I_G(j, :, 2) = \text{cycleleft}(I_G(j, :, 2), x'_R(i)); & \text{when } j \in \text{odd} \& j \leq \frac{L}{2} \text{ or } j \in \text{even} \& j \geq \frac{L}{2}; \\ I_G(j, :, 2) = \text{cycright}(I_G(j, :, 2), x'_B(i)); & \text{otherwise} \end{cases} \quad (10)$$

(b). The direction of the rotation angle for the blue layer is opposite that for the red layer. Specifically, in **Step 2**, the new matrix is rotated by 90 degree to the left, and the shift-controlling parameters are $x'_R(i)$ and $x'_G(i)$. The specific process is shown in Eq. (11).

$$\begin{cases} I_B(j, :, 3) = \text{cycleleft}(I_B(j, :, 3), x'_R(i)); & \text{when } j \in \text{even} \& j \leq \frac{L}{2} \text{ or } j \in \text{odd} \& j \geq \frac{L}{2}; \\ I_B(j, :, 3) = \text{cycright}(I_B(j, :, 3), x'_G(i)); & \text{otherwise} \end{cases} \quad (11)$$

3 The proposed image-encryption

In this section, we present the encryption and decryption processes in detail. The encryption process includes two parts: the confusion process and the diffusion process. A flow chart of the confusion and diffusion processes is shown in Fig. 3. In the confusion process, we utilize the proposed quantification and RCS methods to permute the plain image. In the diffusion process, the image is converted to the bit-plane, and the three percentage values, represented as initial decimals of the PWLCM map, are obtained from the three bit-planes of the colour image. Then, the three corresponding chaotic sequences are calculated to determine the interaction and inter-diffusion of the three layers. Finally, the encrypted image is obtained.

3.1 The process of image encryption

A good encryption scheme should have the following features: (a) It should act directly on an image of any size for the image encryption application, rather than dividing the image into blocks of the same size [25]. (b) It should have a key stream that is strongly related to the plain image. When we encrypt different plain images, the encryption scheme should generate different key streams. The proposed method satisfies these properties, and the size of the colour plain image is assumed to be $M \times N$. The encryption process is given as follows.

- Step 1. The three image layers are extracted using the quantification method proposed in section 2.1, and then the decimal k is obtained as the control parameter a of the skew tent map.
- Step 2. According to the same quantification method, three new groups of decimals, (p_R, q_R) , (p_G, q_G) and (p_B, q_B) , are obtained, in the order from bottom to top and right to left. Then, the three decimals $x_R(1)$, $x_G(1)$ and $x_B(1)$ are generated by Eq. (12), which correspond to the three layers, respectively. Three common image size 256, 512 and 1024 are introduced to be the second parameters in Eq. (12) in order to assure the executive efficiency of the encryption system. $x_R(1)$, $x_G(1)$ and $x_B(1)$ are used as initial values of the skew tent map.

$$\begin{cases} x_R(1) = \left((1 + q_R) \times p_R + \left\lfloor \frac{\text{mod}\left(\sum_{i=1}^M \sum_{j=1}^N I_R(i, j), 256\right)}{256} \times q_R \right\rfloor \right); \\ x_G(1) = \left((1 + q_G) \times p_G + \left\lfloor \frac{\text{mod}\left(\sum_{i=1}^M \sum_{j=1}^N I_G(i, j), 512\right)}{512} \times q_G \right\rfloor \right); \\ x_B(1) = \left((1 + q_B) \times p_B + \left\lfloor \frac{\text{mod}\left(\sum_{i=1}^M \sum_{j=1}^N I_B(i, j), 1024\right)}{1024} \times q_B \right\rfloor \right). \end{cases} \quad (12)$$

Fig. 3 The block diagram of the proposed encryption scheme

- Step 3. The skew map is iterated w ($w = \max(M, N)$) times to produce three sequences $x_R(n)$, $x_G(n)$ and $x_B(n)$.
- Step 4. The chaotic sequences calculated in **Step 3** are quantified by Eq. (13), and then three new sequences $x'_R(n)$, $x'_G(n)$ and $x'_B(n)$ are obtained.

$$x'_{RorGorB}(i) = x_{RorGorB}(i) \times 10^{14} \bmod w + 1 \quad i \in (1, w) \quad (13)$$

- Step 5. The Rubik's Cube Scheme (RCS) from section 2.3 is applied to obtain the scrambled image **I1**.
- Step 6. Transform the image **I1** to bit-plane from the pixel plane, and get three binary matrices (R, G and B). And the percentage of "1" in each bit-plane matrix of **I1** is calculated, and then three decimals are obtained, which are used for the initial values $x_{R1}(1)$, $x_{G1}(1)$ and $x_{B1}(1)$ of the PWLCM system. Then the value η is calculated by using Eq. (14) as the control parameter of the PWLCM map where k comes from **Step 1**.

$$\eta = \left(0.9 \times k + \frac{\bmod \left(\sum_{i=1}^M \sum_{j=1}^N I(i, j), 256 \right)}{256} \times 0.1 \right) / 2 \quad (14)$$

- Step 7. The PWLCM map is iterated $M \times N$ times and the three chaotic sequences $x_{R2}(n)$, $x_{G2}(n)$ and $x_{B2}(n)$ are obtained. After quantifying them using Eq. (15), they are converted into binary arrays. The size of each array is L ($L = M \times N \times 8$). Here, *RorGorB* represents that the same operation is performed for any layer of the color image, and the role of $[x]_2$ is to convert pixel value x to binary data.

$$x''_{RorGorB}(i) = [x_{R2orG2orB2} \times 10^{14} \bmod 256 + 1]_2, i \in (1, M \times N) \quad (15)$$

- Step 8. The three RGB bit-plane matrixes are converted to one-dimensional row vectors $x'_{R2}(n)$, $x'_{G2}(n)$ and $x'_{B2}(n)$. Then, the three RGB row vectors are inter-encrypted as follows.

The sequences $x'_G(n)$ and $x'_B(n)$ are used as control parameters for the red layer XOR operations. The first entry of the red layer row vector is encrypted by Eq. (16), and then the i th entry is encrypted as shown in Eq. (17).

$$Ex''_{R2}(1) = x''_{R2}(1) \oplus x''_{R2}(L) \oplus x''_G(1) \oplus x''_B(1) \quad (16)$$

$$Ex''_{R2}(i) = x''_{R2}(i) \oplus x''_{R2}(L-i) \oplus x''_G(i) \oplus x''_B(i) \quad (2 \leq i \leq L) \quad (17)$$

The green and blue layer encryptions are similar to that of the red layer, with different parameters. The bit-XOR operations are shown in Eq. (18–19) and Eq. (20–21), respectively.

$$Ex''_{G2}(1) = x''_{G2}(1) \oplus x''_{G2}(L) \oplus x''_R(1) \oplus x''_B(1) \quad (18)$$

$$Ex''_{G2}(i) = x''_{G2}(i) \oplus x''_{G2}(L-i) \oplus x''_R(i) \oplus x''_B(i) \quad (2 \leq i \leq L) \quad (19)$$

$$\mathbf{E}x_{B2}''(1) = x_{B2}''(1) \oplus x_{B2}''(L) \oplus x_R''(1) \oplus x_G''(1) \quad (20)$$

$$\mathbf{E}x_{B2}''(i) = x_{B2}''(i) \oplus x_{B2}''(L-i) \oplus x_R''(i) \oplus x_G''(i) \quad (2 \leq i \leq L) \quad (21)$$

Step 9. Finally, we obtain three binary sequences. The image of size $M \times N$ is recovered in the pixel-plane, and the encrypted colour image $\mathbf{E}$ is finally obtained.

After these steps, the plain image is completely encrypted. In the decryption process, these steps are applied in reverse order which is given in next subsection.

3.2 The process of image decryption

- Step 1. First, the three sequences $x_R'(n)$, $x_G'(n)$ and $x_B'(n)$ are obtained according to the **Step 6** and **Step 7** in section 3.1.
- Step 2. The cipher image is processed by one round of bit-XOR operations, as in the method described in **Step 8** of section 3.1 but in reverse order.
- Step 3. Then, we get three chaotic integer sequences $x_R'(n)$, $x_G'(n)$ and $x_B'(n)$ according to **Step 1-Step 5** in section 3.1.

Similarly, the number of rows of the processed image at any stage is L . The decryption process of the red layer of the image is given by:

- (a). Set $i = w$. The j th ($j \in \text{even} \& j \leq \frac{L}{2}$ or $j \in \text{odd} \& j \geq \frac{L}{2}$) row of the red layer matrix is cycle-shifted to the right $x_G'(i)$ times, so the other rows are cycle-shifted to the left $x_B'(i)$ times.
- (b). After the cycle-shift, the generated matrix for the red layer is rotated 90 degree to the left.
- (c). Let $i = i - 1$, and then repeat **(a)** and **(b)**.
- (d). When $i < 1$, the decryption operation of the red layer is complete.

The direction of cycle-shifted for the green layer is opposite that of the red layer, and the controlling parameters are $x_R'(i)$ and $x_B'(i)$, respectively. The direction of the rotation angle for the blue layer is opposite that for the red layer, and the controlling parameters are $x_R'(i)$ and $x_G'(i)$, respectively. Then, through confusion and diffusion in the corresponding reverse order, we obtain the decrypted image.

4 Experimental results

To test the performance of the proposed algorithm, the experiments are carried out and the results are given in this section. We use the three standard 512×512 colour images shown in Fig. 4 (a-c) as the input images (the images are “jpg” format). The experiment is run in MATLAB 2014a. Then, the permuted images are shown in Fig. 4 (d-f), the encrypted images are shown in Fig. 4 (g-i), and the decrypted images are shown in Fig. 4 (j-l). Of course, the experimental results show that the algorithm is also applicable to other image formats such as “png”, “bmp” and “tiff”. A good encryption algorithm should resist all known kinds of attacks, such as exhaustive attacks, differential attacks and statistical attacks. In addition, the key space

should be large enough to resist brute-force attacks and should be sensitive to the secret keys. Therefore, in the following subsections, several tests are discussed to check the security of the proposed cryptosystem.

4.1 Key space analysis

High sensitivity to initial conditions is an inherent characteristic of any chaotic system. To provide an encryption algorithm with high security, the key space should be large enough to make any brute-force attack ineffective. There are two chaotic systems contained in the proposed cryptosystem: the skew tent map and PWLCM map. The skew tent map contains a control parameter a and initial parameters $x_R(1)$, $x_G(1)$, and $x_B(1)$, and the PWLCM map contains these parameters η , $x_{R1}(1)$, $x_{G1}(1)$ and $x_{B1}(1)$. If the precision is 10^{-15} , the key space will be $(10^{15})^8 \approx 2^{400}$. In

Fig. 4 Original, permuted, encrypted and decrypted images: (a), (d), (g), (j) Lena; (b), (e), (h), (k) Baboon; (c), (f), (i) (l) Peppers

addition, these parameters are be strictly related with the plain image, so the key space is much larger than 2^{400} , which is large enough to prevent exhaustive searching. Thus, the proposed algorithm is fully capable of resisting any brute-force attack.

4.2 Key-sensitivity analysis

A good encryption algorithm should be sensitive to the secret key. In other words, a very small change in the secret key will result in a huge change in the encrypted image. In the proposed algorithm, we calculated the tent map initial control parameter $a = 0.412734985351563$ to encrypt the 512×512 Lena colour image in section 2.1. We change the parameter to $a = 0.412734985351564$, which is just one bit different from the initial value, and keep other keys unchanged. The images encrypted with the correct and incorrect keys are shown in Fig. 5 (a)

Fig. 5 The key-sensitivity results. (a) is original cipher image; (b) is cipher image with a slight change in the initial key; (c) shows the differences between the original cipher image (a) and image (b); (d) is the red layer of image (c); (e) is the green layer of image (c); (f) is the blue layer of image (c); (g)-(i) are the grey histograms of image (d)-(f), respectively

and Fig. 5 (b), respectively. The difference between the two encrypted images is shown in Fig. 5 (c), and the corresponding NPCR and UACI values are 99.63% and 33.54%, respectively. Figure 5 (d), (e) and (f) are red, green and blue layers of Fig. 5 (c), respectively. Fig. 5 (g), (h) and (i) are the histogram of Fig. 5 (d), (e) and (f), respectively. Similar sensitivity results are obtained when we change the other parameters by only one bit. This clearly demonstrates that the proposed cryptosystem is highly sensitive to the secret key.

4.3 Differential attack

Attackers often make small changes to the original image and then encrypt the image using the proposed algorithm to determine the relationship between the original image and the cipher image. Therefore, the cryptosystem should be sensitive to the plain image to resist the differential attack. Some quantitative measures are the number of pixels change rate (NPCR) and the unified average changing intensity (UACI). These are used to test the influence of a small change on the whole cipher image. $NPCR_{R, G, B}$ and $UACI_{R, G, B}$ are defined as follows.

$$NPCR_{R, G, B} = \frac{\sum_{i,j} D_{R, G, B}(i, j)}{M \times N} \times 100\%, \quad (22)$$

where M and N are the width and height of the cipher image, $E_{R, G, B}$ and $E'_{R, G, B}$ are the two cipher images whose corresponding plain images differ by only one bit. The difference array $D_{R, G, B}(i, j)$ is determined by the following rule: when the pixels in position (i, j) in $E_{R, G, B}$ and $E'_{R, G, B}(i, j)$ are different (i. e. $E_{R, G, B} \neq E'_{R, G, B}(i, j)$), then $D_{R, G, B}(i, j) = 1$; otherwise, $D_{R, G, B}(i, j)$ is 0. The probability distribution of $D_{R, G, B}(i, j)$ is

$$D_{R, G, B}(i, j) = \begin{cases} 0, & \text{if } E_{R, G, B}(i, j) = E'_{R, G, B}(i, j), \\ 1, & \text{if } E_{R, G, B}(i, j) \neq E'_{R, G, B}(i, j). \end{cases} \quad (24)$$

In this test, the size of the colour image is 256×256 , the quantitative measures NPCR and UACI are calculated for three different plain images as shown in Fig. 4 (a), (b) and (c), respectively, and their results are shown in Table 1. The tested pixels are located at (1, 1) in each image.

From Table 1, the average values of NPCR and UACI are 99.6262% and 33.5586%, respectively. 100 pixels from the red layer of the “Lena” image (256×256) are randomly selected, and each pixel’s lowest bit is changed successively to obtain 100 different images. Then, we calculate the values of NPCR and UACI as shown in Fig. 6. We clearly find that the means of these 100 tests for NPCR and UACI are 99.6235% and 33.5378%, respectively. Moreover, the different encryption algorithms are compared and the NPCR and UACI values

Table 1 NPCR and UACI for different plain images

Image	NPCR (%)			UACI (%)		
	Red	Green	Blue	Red	Green	Blue
Lena	99.6201	99.6445	99.6140	33.5903	33.5229	33.6609
Baboon	99.6490	99.6154	99.6017	33.5236	33.5441	33.5511
Peppers	99.6231	99.6221	99.6419	33.5112	33.5597	33.5634

Fig. 6 The results of (a) NPCR and (b) UACI for all modified plain images using the Lena as an example

are shown in Table 2. From Table 2, we can see that the proposed algorithm is capable of resisting differential attacks.

Besides, if there is no the quantization process, the parameter $k = 0.2$ is fixed for the encryption algorithm to experiment and test. Similarly, the 100 pixels of the plain-image Lena are randomly changed to test the differential attack, i.e., the numbers of NPCR for these 100 times of experiments without the quantization process but only a fixed k are obtained, and they are shown in Fig. 7 to compare with the results above. The results show that the proposed quantization process can effectively enhance the sensitivity of the encryption algorithm to plain image.

In addition, in order to further test this effect of the quantization process, other plain images Baboon and Peppers are also experimented the same test. The experimental results are shown in Figs. 8 and 9, respectively. From the figures it can be clearly seen that there is a good performance as well. Therefore, these results illustrate that the quantization process can improve the security of encryption algorithm to certain extent.

Table 2 Comparative study of NPCR and UACI of the proposed algorithm vs. existing algorithms

Parameters	Ours	Ref. [23]	Ref. [36]	Ref. [42]	Ref. [43]	Ref. [5]	Ref. [29]
NPCR (%)	99.6235	99.6109	99.6475	99.6000	99.6300	99.6167	99.3700
UACI (%)	33.5378	33.4739	33.3343	33.4800	33.3700	33.4500	33.4500

Fig. 7 The comparative NPCR values of the differential attack for plain image “Lena” with the quantization process and without the quantization process

4.4 Information entropy

Information entropy can be used to describe the complexity and randomness of the encryption system. Let m be the information source, the information entropy can be calculated by:

$$H(m) = \sum_{i=0}^{2^n-1} p(m_i) \log_2 \frac{1}{p(m_i)} \quad (25)$$

where $p(m_i)$ represents the probability of symbol m_i . For a random image with 256 grey levels, assume any grey level appears with the same probability. According to Eq. (25), we can achieve the ideal $H(m)=8$, which shows that the information is random. The closer the information entropy of the cipher image is to 8, the higher the randomness of the cryptosystem. We calculate the information entropies of the cipher images in Fig. 4 (g), (h), and (i). The results are shown in Table 3. The entropy values are all very close to the ideal value of 8, and the proposed scheme performs better than the other schemes.

Fig. 8 The comparative NPCR values of the differential attack for plain image “Baboon” with the quantization process and without the quantization process

Fig. 9 The comparative NPCR values of the differential attack for plain image “Peppers” with the quantization process and without the quantization process

4.5 Statistical analysis

4.5.1 The histogram analysis

The histogram of an image reflects the contribution of each grey level. In general, the distribution of an ordinary plain image is nonuniform, and some values have high frequencies. Hence, it can be exploited easily due to the amount of useful information exposed. To resist such attacks, the histogram of the encrypted image should be uniform. The histograms of the plain image Fig. 4 (a) and cipher image Fig. 4 (d) are shown in Fig. 10. Comparing the histograms before and after encryption, we clearly find that the histogram of the encrypted image is very uniform and significantly different from that of the corresponding plain image.

4.5.2 Correlation-coefficient analysis

A plain image usually contains a lot of information due to the strong correlations between adjacent pixels. In general, the high correlations among adjacent pixels for an ordinary image exist in the horizontal, vertical and diagonal directions. Therefore, a good encryption algorithm should remove these correlations as soon as possible. The correlation property can be quantified by means of correlation coefficients as

Table 3 Comparative study of the entropy of the proposed algorithm vs. some existing algorithms

Algorithms	$H(m)$
This work (Lena)	7.9998
This work (Baboon)	7.9997
This work (Peppers)	7.9998
Ref. [15]	7.9992
Ref. [49]	7.9993
Ref. [20]	7.9993
Ref. [43]	7.9970
Ref. [5]	7.9977
Ref. [29]	7.9920

Fig. 10 (a)–(c) the histograms of initial colour image “Lena” for the red, green and blue layers, respectively. (d)–(f) the histograms of the cipher image for the red, green and blue layers, respectively

$$r_{xy} = \frac{\text{cov}(x, y)}{\sqrt{D(x)D(y)}} \quad (26)$$

where x and y are grey scale values of two adjacent pixels, and

$$E(x) = \frac{1}{N} \sum_{i=1}^N x_i \quad (27)$$

$$D(x) = \frac{1}{N} \sum_{i=1}^N (x_i - E(x))^2 \quad (28)$$

$$\text{cov}(x, y) = \frac{1}{N} \sum_{i=1}^N (x_i - E(x))(y_i - E(y)) \quad (29)$$

where x_i and y_i are two adjacent pixels in the image, N is the total number of adjacent pixel pairs (x_i, y_i) , and $E(x)$ and $E(y)$ are the mean values of x_i and y_i , respectively. First, we randomly select 10^4 pairs adjacent pixels of “Lena” in the vertical, horizontal and diagonal

directions from the plain and cipher images. The results as shown in Fig. 11. It is obvious that the plain image has a strong correlation among adjacent pixels. However, the correlation in corresponding the cipher image becomes less relevant.

Then, the correlation coefficients of all three plain-images and their corresponding cipher images in vertical, horizontal and diagonal directions are calculated and shown in Table 4. It is clear that all correlation coefficients of the plain image are close to 1,

Fig. 11 Distributions of two adjacent pixels in the plain image and in the cipher image

Table 4 Correlation coefficients of plain and cipher images

Image	Direction of correlation coefficient					
	Horizontal		Vertical		Diagonal	
	Plain	Cipher	Plain	Cipher	Plain	Cipher
Lena	0.9712	0.0046	0.9783	0.0043	0.9547	-0.0006
Baboon	0.9437	0.0017	0.9212	-0.0036	0.9002	0.0029
Peppers	0.9654	-0.0010	0.9552	0.0042	0.9142	0.0025

while those of the cipher image are close to 0 and the values are similar. Therefore, the proposed algorithm can effectively remove the correlations among adjacent pixels in the plain image, and it is strong enough to resist statistical attacks. The results are compared to those of other schemes in Table 5, and the comparison results further prove that the proposed algorithm is better.

4.6 Occlusion and noise attack analysis

Occlusion-attack analysis is very important for testing the robustness of the cryptosystem [11]. As for occlusion attack, we are known that the cipher image is partially damaged during the transmission process, and the larger the data loss, the higher the distortion. If the damaged cipher image can be recovered successfully, the encryption scheme would be considered to have the ability to defend against the occlusion attack [23]. Figure 12 (a)-(h) shows different occluded cipher images, in which 100 columns or 100 rows are destroyed in Fig. 12 (a)-(d), 150×150 pixels from the four corners of the cipher-image and 212×212 pixels selected from the centre of the cipher-image are destroyed shown in Fig. 12 (e) and Fig. 12 (f), respectively. After decryption, we obtain their corresponding decrypted images shown in Fig. 12 (m)-(n). From the decrypted results, it can be seen that the decrypted images can clearly reflect the information of the original image despite of the existing occlusion attack. To further test the robustness of the algorithm, the cipher-image is further occluded with 75% in the left and right of the image shown in Fig. 12 (g), and the decrypted imaged shown in Fig. 12 (o). It can be seen that the decrypted images can still be clearly recognized

Table 5 Comparative study of the average correlation coefficients of the proposed algorithm vs. some existing approaches

Algorithms	Direction of correlation coefficient		
	Horizontal	Vertical	Diagonal
This work	0.0021	0.0036	-0.0018
Ref. [15]	0.0265	0.0792	0.0625
Ref. [20]	0.0064	0.0078	0.0029
Ref. [25]	-0.0046	0.0010	0.0078
Ref. [48]	0.0113	-0.0013	0.0310
Ref. [1]	-0.0126	-0.0050	-0.0012

Fig. 12 The decrypted images under different occlusion attacks

even though a strong occlusion attack has occurred. However, occlusion attacks on the image-signal transmission usually happen random. Therefore, the cipher-image is randomly occlude with 80% shown in Fig. 12 (h), and the decrypted image shown in Fig. 12 (p) can be clearly recognized as well. These results prove that the proposed cryptosystem has sufficient capability to resist occlusion attacks.

On the other hand, the Gaussian noise and Salt and pepper noise are two common noises to be experimented to test the noise attack, and the experimental results are shown in Figs. 13 and 14, respectively. The results demonstrate that the proposed scheme has a strong robustness to resist against the external interference, such as occlusion attack and noise attack.

4.7 Chosen/known plain-image attacks

In our algorithm, we use the following strategies to effectively avoid chosen/known plain-image attacks. (a) In the confusion process, we use the novel RCS algorithm to

Fig. 13 Gaussian noise attack analysis: (a)-(c) cipher-images with different levels of noise Mean = 0, Variance = 0.05; Mean = 0, Variance = 0.15; and Mean = 0, Variance = 0.25; (d)-(f) the corresponding decrypted images

permute the image. The image rotation angle and the number of pixel cycle-shifts are stochastically decided by chaotic sequences, so the process exhibits strong randomness and robustness; (b) The confusion and diffusion processes can be realized at the same time. Therefore, the proposed algorithm can resist a divide-and-conquer attack [25]; and (c) The initial keys are closely related to the plain image, as discussed in section 2.1; the secret keys are completely different for different plain images. Hence, our algorithm has enough ability to resist known plain-image attacks.

Fig. 14 Salt and pepper noise attack analysis: (a)-(c) cipher-images with Noise density = 5%, Noise density = 10%, and Noise density = 20%, and (d)-(f) the corresponding decrypted images

Table 6 Execution times of the proposed system (unit: s)

Process	The quantification process	The RSC process	Int2Bin Converter	Bit-plane XOR process	Bin2Int Converter	Total
Time	0.143392	1.468294	0.445377	1.687679	0.467728	4.212

4.8 Speed analysis and comparisons

In this section, we discuss the speed performances of the proposed algorithm. To evaluate the proposed scheme and comparable algorithms, different sizes of the standard colour image “Lena”, namely, 256×256 , 512×512 , and 1024×1024 , are selected. The software environment is MATLAB 2014a on the Windows 7 system; the hardware environment includes 2GB RAM, a 2.6 GHz Pentium processor, and 2GB memory. The execution is tested 100 times. The mean test time of every step is listed in Table 6, and the pie chart in Fig. 15 shows that the RSC process and the XOR process occupy 35% and 40% of the total time, respectively, and the other processes take up 25% of the total time.

The average encryption time of different size of the colour image and grey image as the Table 7 shows. In addition, Tables 8 and 9 show the results of the speed performance test, and we clearly find that the encryption speed of our algorithm is faster than other algorithms.

Specifically, the proposed quantization scheme is compared with the other methods in Ref. [23] and Ref. [25]. Experimental results show that their quantification time is 0.165513 s and 0.085639 s, respectively, which shows that the proposed quantization scheme has a relatively good performance because its execution speed is faster than that in Ref. [23] and the plaintext sensitivity is better than that in Ref. [25] although the quantification time is a little higher.

Besides, the permutation method has been compared with other common methods in the previous work [24], i.e., coupled map lattice (CML) [39], ergodic matrix (EM) [36], constructed two ergodic sequences (CTES) [23], and dynamic random growth technique (DRGT) [40], by using the tests of percentage of adjacent pixels count (PAPC), distance between adjacent pixels (DBAP), the fixed point analysis, correlation analysis, and the permutation time analysis to illustrate Rubik’s Cube Scheme has a better performance and is more suitable for image encryption.

Fig. 15 Average encryption time of each component as a percentage of the total time of the proposed algorithm for “Lena” (size: 256×256)

Table 7 Average encryption times of the proposed algorithm

Image size (pixels)	256 × 256	512 × 512	1024 × 1024
Colour image	4.212(s)	8.308(s)	16.254(s)
Grey image	1.318(s)	2.256(s)	5.249(s)

Table 8 Comparative study of the encryption time of the proposed algorithm vs. other existing gray image encryption algorithms

Image size (pixels)	Our algorithm	Ref. [23]	Ref. [19]	Ref. [13]	Ref. [2]
256 × 256	1.318 (s)	1.670 (s)	3.704(s)	3.284 (s)	2.901 (s)

Table 9 Comparative study of the encryption time of the proposed algorithm vs. other existing color image encryption algorithms

Image size (pixels)	Our algorithm	Ref. [38]	Ref. [30]	Ref. [44]
512 × 512	8.308 (s)	16.170 (s)	8.670(s)	33.418(s)

5 Conclusion

In this paper, we proposed an efficient and self-adapting colour-image encryption algorithm based on chaos and interactions among multiple layers. Based on the plain image, a decimal between (0, 1) is obtained and quantified to be used as the initial value of the skew tent map and PWLCM map. In the confusion process, a novel RCS algorithm is proposed to achieve inter-scrambling of the three layers. Similarly, the multiple layers are involved in the inter-encryption of the diffusion process. The experimental results and analyses indicate that the proposed algorithm can not only perform encryption operation but also has high robustness to resist most of known attacks, e.g. statistical analysis, differential attacks and exhaustive attacks, which indicate that the proposed algorithm can be used for digital image encryption.

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