A Space-bit-plane Scrambling Algorithm for Image Based on Chaos

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Abstract—Image scrambling is an important technique in digital image encryption and digital image watermarking. This paper’s main purpose is to research how to scramble image by space-bit-plane operation (SBPO). Based on analyzing traditional bit operation of individual pixels image scrambling method, this paper proposed a new scrambling algorithm. The new scrambling algorithm combined with SBPO and chaotic sequence. First, every eight pixels from different areas of image were selected according to chaotic sequence, and grouped together to form a collection. Second, the SBPO was performed in every collection and built eight pixels of the image with new values. The scrambling image was generated when all pixels were processed. In this way, the proposed algorithm transforms drastically the statistical characteristic of original image information, so, it increases the difficulty of an unauthorized individual to break the encryption. The simulation results and the performance analysis show that the algorithm has large secret-key space, high security, fast scrambling speed and strong robustness, and is suitable for practical use to protect the security of digital image information over the Internet.

Index Terms—image scrambling, image encryption, chaotic sequence, logistic map, space-bit-plane operation (SBPO)

I. INTRODUCTION

Along with the rapid development of Internet and the multimedia technologies, the transmission of the digital image with private or business information is more ubiquitous, so the security problem of digital image has been highlighted. Currently, the image encryption technology has become a very important approach to enhance the image transmission security. Image scrambling is not only a usual image encrypt method, but also a preprocessing of data watermark and image hiding. For instance, transform a meaningful image into a meaningless or disordered image to increase its ability to resist invalid attack and in turn enhance the security. Images are different from texts in many aspects, such as highly redundancy and correlation, the local structure and the characteristics of amplitude frequency. As a result, the methods of conventional encryption perhaps cannot be applicable to images.

Most of the earlier proposed image scrambling schemes were based on position permutation method, such as Arnold transformation [1]-[2], Hilbert curve transformation [3], and knight-tour transformation etc [4]. This kind of schemes were not changed the image gray histogram after scrambling, which do not satisfy the requirement of modern cryptography. Besides, position permutation-only schemes are insecure against known/chosen-plaintext attack, for the histogram is a measure of the important characteristics of an image, the attacker can use the gray histogram to obtain the original image’s approximate content [5]. In addition to, these methods restricted to image size specification and need multiple iterations. Therefore, in order to improve the efficiency of image scrambling encryption and security, there are many effective algorithms have been proposed.

Chaotic system is a deterministic nonlinear system that has many important properties, such as aperiodic, sensitive dependence on initial conditions and system parameters, density of the set of all periodic points and topological transitivity, etc. It provides a new approach for cryptography and a large number of chaos-based image cryptosystems have been suggested and investigated during the past decade. The basic idea of chaos-based image scrambling scheme is implementation both position permutation and grayscale substitution on an image by using chaotic key stream and the security depends on the unpredictability of the pseudorandom key stream. The chaos-based image scrambling scheme has the advantages of strong against known/chosen plaintext attack and fast scrambling speed. However, the concrete implementation of a chaos-based scrambling system is by far ideal as the abstract model with infinite and not even countable cardinality [6].
Some image scrambling schemes are based on binary bit plane decomposition [7]. Bit plane decomposition is a process to decompose the grayscale image into n binary images called n bit planes. The order of the bit planes is from the most significant bit to the least significant bit. Each bit plane consists of all binary bits with the same order in the n-bit binary sequences of all pixels. However, this type of decomposition process has low security level since it is not parameter-dependent [8].

In Ref. [9], Zhang and Cai exploited an image encryption algorithm based on bit-plane scrambling with multiple chaos systems, it can shuffle the positions and change the grey values of image pixels simultaneously. Although the method could achieve better scrambling effect, but the corresponding scrambling operation was also more complicated.

In this paper, we propose a new image scrambling method which based on space-bit-plane operation (SBPO) and chaotic sequence. First, every eight pixels from different areas of image were selected according to chaotic sequence, and grouped together to form a collection. Second, the SBPO was performed in every collection and build eight pixels of the image with new values. And finally the scrambling image was generated when all pixels were processed. This algorithm is easy to operate and it can deal with color image and gray image. In addition to, the square image and the non-square image can also be processed. Moreover, the scrambling process by SBPO is not only changed the pixel’s position but also the value. The corresponding probability of each pixel’s value is also changed. So, the gray histogram of the scrambled image obvious is different from original image histogram. Thus, the scrambled image appears in the white noise form to enhance the security of image transmission.

The rest of this paper is organized as follows. We discuss the logistic chaotic map and the principle of the SBPO in Sections II and III, respectively. In Section IV, we shall present the proposed image scrambling algorithm. Experimental results and security analyses of the scheme will be reported in Section V. Finally, concluding remarks will be made in Section VI.

II. LOGISTIC CHAOTIC MAP

Since Robert A. J. Matthews presented the concept of chaotic cipher in 1989, chaotic encryption method has attracted more and more attention.

A discrete time dynamical system can be defined as following equation:

$$X_{k+1} = f(\mu, X_k)$$  \hspace{1cm} (1)

Where $f$ is a nonlinear function, and $\mu$ denotes its parameter, $X_k \in \mathbb{R}^n$ and $0 < X_k < 1 (k=0,1,2,\ldots)$. If we repeatedly apply it to an initial condition $X_0$, then we will get a sequence $\{X_k: k=0,1,2,\ldots\}$.

The typical chaotic dynamical systems, such as logistic map, Lorenz system and tent map, etc, that can be used for image scrambling. One-dimensional (1-D) logistic system is due to simplicity and efficiency, which widely has been used now. It’s mathematical expressed as:

$$X_{k+1} = \mu X_k (1 - X_k)$$  \hspace{1cm} (2)

Where $0 < \mu \leq 4$ is called bifurcation parameter and $X_k$ is define as above. It has been proved that when $3.5699456 < \mu \leq 4$, logistic map will operate in chaotic state. That is to say, $\{X_k: k=0,1,2,\ldots\}$ is produced with initial condition $X_0$ will be non-periodic, non-converging and non-correlated [10].

The probability density function of logistic map can be described as follows, which is shown in Fig. 1.

$$p(x) = \begin{cases} 
\frac{1}{\pi \sqrt{1 - x^2}} & -1 < x < 1 \\
0 & \text{else}
\end{cases} \hspace{1cm} (3)$$

Figure 1. Probability density of Logistic map.

From Fig. 1 we can see, the probability density of Logistic map is symmetric, $p(x)$ does not depend on the initial value $X_0$, indicating that the chaos system is ergodic. The advantages of chaotic sequences can be concluded as follows:

- Sensitive to initial conditions. A small difference in initial conditions will lead to a significant difference of chaotic sequences. That is important from the view of security.
- Easy to generate. Chaotic sequences are generated with fast speed and low computing complexity.
- Noise-like. Some statistical characteristics of chaotic sequence are the same as white noise, which make it has good randomness.

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III. THE PRINCIPLE OF THE SBPO

A. Pixel Bit Planes Decomposition

The L-bits image is denoted as \( A(m, n) \) with the size of \( M \times N \), where \( m=0,1,\ldots,M-1 \) and \( n=0,1,\ldots,N-1 \). Image \( A \) was decomposed into L-bits plane, each pixel in every bit-plane corresponds to 0 or 1.

**Definition 3.1**: Assumed that \( B^l(\cdot) \) represents bit decomposition operator, so the \( l \)-bit of \( A(m, n) \) is represented as \( a^l(m,n) \):

\[
\begin{align*}
a^l(m,n) &= B^l(A(m,n)) = \\
&= \begin{cases} 
1 & \text{if } \left\lfloor \frac{A(m,n)}{2^l} \right\rfloor \mod 2 = 1 \\
0 & \text{otherwise}
\end{cases} 
\end{align*}
\]

(4)

Took a 8-bits gray image of 256×256 as experimental images, then results of bit decomposition are showed as Fig.2.

\[
A(m,n) = \sum_{l=0}^{L-1} 2^l \times a^l(m,n)
\]

(5)

From Fig. 2 we can see, with the bit plane from the high to the low (from bit plane 8 to bit plane 1), the outline of the image is gradually blurred, the useful information gradually reduced. From the bit plane 4 starting is almost no image information, the bit plane 1 carry the least amount of information.

B. SBPO

Many scrambling algorithm used image exchange operations on bit-plane, but only did a bit-exchange operation on single pixel or adjacent pixels. Considering the digital image adjacent pixels have strong relevance, especially for the image that appears a large area of pixel value completely equal, there is no difference for the values of image pixels after bit-exchange operation on single pixel or adjacent pixels.

There are many collections exist in the image, they represent different information, so we can distinguish different images or different parts of the same image. Only greatly reduce the correlation between pixels, to undermine the information of these collections, we can achieve better image scrambling effect, in other words, to achieve uniform scrambling. To break the correlation between pixels, we shall be dispersed adjacent pixels as far as possible. Therefore, a new bit-exchange operation was proposed, that is, the SBPO. The SBPO was carried out multiple collections with eight pixels, which were selected from different areas of the image according to the space information generated by the chaotic sequence.

**Definition 3.3**: For a eight-pixels collection \( A = \{A_1, A_2, A_3,\ldots, A_8\} \) from the 8-bits image, the following operation is called SBPO.

Using (4) each pixel of \( A \) could be decomposed 8-bits, constituted a two-dimensional (2-D) matrix with the size of \( 8 \times 8 \).
These elements in the Λ were used the SBPO and got a new 2-D matrix A' with the size of $8 \times 8$. This formula could be expressed as:

$$A'(i, 9 - j) = A \text{mod}(i - 1 + j, 8), j \quad (7)$$

where $i \in \{1, 2, ..., 8\}$, $j \in \{1, 2, ..., 8\}$, the new matrix A' could be expressed as:

$$A' = \begin{bmatrix}
a_{88} & a_{18} & a_{28} & a_{38} & \cdots & a_{78} 
a_{77} & a_{87} & a_{17} & a_{27} & \cdots & a_{67} 
a_{66} & a_{76} & a_{86} & a_{16} & \cdots & a_{56} 
a_{55} & a_{65} & a_{75} & a_{85} & \cdots & a_{45} 
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots 
a_{11} & a_{21} & a_{31} & a_{41} & \cdots & a_{81} 
\end{bmatrix} \quad (8)$$

where each pixel of $\{A'_i: i = 1, 2, ..., 8\}$ can be reconstructed by (5).

From (8) we can see that the SBPO is space cycle bit shift for eight pixels from different parts of the image. After the SBPO, we got new eight pixels, each that blended the other pixels values. In addition to, the SBPO also exchanged of the high bit-plane value and the low bit-plane value. Therefore, after all collections with eight pixels included in the image were carried out the SBPO, these new pixels values were greatly changed, so the correlation between pixels was greatly reduced, that is, the distribution of the new image pixel value was very uniform. Less relation between the original image and the scrambled one, and higher efficiency of the scheme can be obtained.

The advantages of the SBPO can be concluded as follows:

- Better uniformity of scrambling. The SBPO was carried out the pixels from different regions, which make the scrambling image has good uniformity. It can scramble the image that appears a large area of pixel value completely equal.

IV. THE PROPOSED IMAGE SCRAMBLING ALGORITHM

Assume that a 8-bits gray image F contains $m \times n$ pixels each having a pixel value $f(i, j)$, where $i$ and $j$ are the coordinates of the pixel. The scrambled image S still contains $m \times n$ pixels. Fig. 3 shows the scrambling and the unscrambling algorithm of image.

A. Scrambling Algorithm

The whole scrambling steps were as follows:

**Step1:** Took the Logistic equation as the model, input key1 (starting value of $\mu$) and key2 (starting value of $X_0$), used (2) produced real value chaotic sequence $\{X_i: i = 1, 2, ..., m \times n\}$. The chaotic sequence was divided into 8 short sequences $\{y_i: i = 1, 2, ..., 8\}$ which length were all $(m \times n)/8$, where

$$y_i = \left\{ \frac{X}{(i - 1) \times \frac{m \times n}{8}}, \frac{X}{(i - 1) \times \frac{m \times n}{8}}, ..., \frac{X}{(i - 1) \times \frac{m \times n}{8}} \right\}, i \in \{1, 2, ..., 8\} \quad (9)$$

**Step2:** Converted the original image F’s pixel matrix into a 1-D sequence $\{P_i: i = 1, 2, ..., m \times n\}$. The sequence was divided into 8 short sequences $\{z_i: i = 1, 2, ..., 8\}$ which length was $(M \times N)/8$, where

$$z_i = \left\{ \frac{P}{(i - 1) \times \frac{M \times N}{8}}, \frac{P}{(i - 1) \times \frac{M \times N}{8}}, ..., \frac{P}{(i - 1) \times \frac{M \times N}{8}} \right\}, i \in \{1, 2, ..., 8\} \quad (10)$$

**Step3:** Sorted the sequence $y_i = \{X_1, X_2, ..., X_{m \times n}/8\}$ from small to large, and got the sorted sequence $y'_i = \{X'_1, X'_2, ..., X'_{m \times n}/8\}$. Using the same sort operation as sequence $y_i$ to sort sequences $\{y_i: i = 2, 3, ..., 8\}$, and got the other seven sorted sequences $\{y'_i: i = 2, 3, ..., 8\}$.

**Step4:** Calculated the set of scrambling address codes $M_i = \{m_i, m_2, ..., m_8(M \times N)/8\}$, where $i \in \{1, 2, ..., 8\}$. M, was

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the new subscript of \( \{ y_i : i=1,2,\ldots,8 \} \) in the sorted sequence \( \{ y'_i : i=1,2,\ldots,8 \} \), which included space information that would be used to select pixels in image.

**Step5:** According to the first address code in every set of scrambling address codes \( \{ M_i : i=1,2,\ldots,8 \} \) to select eight pixels respectively from \( \{ z_i : i=1,2,\ldots,8 \} \), then grouped together to form a collection with eight pixels. So, these eight pixels came from different areas of image, of which existed great difference.

**Step6:** Using the same method to select pixels based on every other address codes in \( \{ M_i : i=1,2,\ldots,8 \} \) form other collections. After all the address codes were being used in the \( \{ M_i : i=1,2,\ldots,8 \} \), select pixel’s work was done, which formed collections \( \{ D_i : i=1,2,\ldots,(m \times n)/8 \} \), each sub-set contained 8 pixels.

**Step7:** On each sub-set of the \( \{ D_i : i=1,2,\ldots,(m \times n)/8 \} \) using (6), (7) and (8), that is, using the SBPO, to get corresponding new set \( \{ D'_i : i=1,2,\ldots,(m \times n)/8 \} \).

**Step8:** All of sub-set in \( \{ D'_i : i=1,2,\ldots,(m \times n)/8 \} \) were connected together to form a new 1-D sequence \( \{ P'_i : i=1,2,\ldots,m \times n \} \), and then transformed 1-D sequence \( P' \) into 2-D matrix \( S \) with the size of \( m \times n \), the \( S \) was the scrambled image.

Simple extension of the above algorithm, we can scramble 24-bits color image. We applied the same chaotic sequence and the SBPO, but in this case we would scramble according to the above procedure on three components (R, G and B) of color image separately.

### B. Unscrambling Algorithm

From Fig. 3 we can see, the image pixels positions scrambling and the SBPO were the reversible operation, so that the scrambled image’s unscrambling was the image scrambling counter process. This paper no longer gives unnecessary details.

### V. EXPERIMENTAL RESULTS AND SECURITY ANALYSES

In order to test the performance of the scrambling method, this paper used MATLAB to simulate this algorithm. Took a gray image of \( 256 \times 256 \), a gray image of \( 144 \times 256 \) and a color image of \( 256 \times 256 \) as experimental images, let key1=3.9988, key2=0.5 and the way of space cycle bit shift in (7) as the secret-key. Then results of scrambling are showed as Fig. 4 - Fig. 6.

Figure 4. Original, scrambling and normal unscrambling 8-bits gray image \((256 \times 256)\): (a) Original image, (b) scrambling image, (c) normal unscrambling image.

Figure 5. Original, scrambling and normal unscrambling 8-bits gray image \((144 \times 256)\): (a) Original image, (b) scrambling image, (c) normal unscrambling image.
From the experimental results we can see that, the scrambled images have completely changed the characteristics of the original images, and there are no difference between the unscrambled images and the original images in the visual, the purpose of image scrambling has been achieved.

In addition to, from Fig. 4 - Fig. 6 we can see that this method can scramble color image and gray image. Moreover, the square image and the non-square image can also be processed.

A. Secret-key Security Sensitivity Analysis

Higher security level of the scrambled image can be achieved since the method has at least three security secret-keys (key1, key2 and the way of space cycle bit shift) and all the security secret-keys have many possible choices.

We unscramble the scrambled image (Fig. 1(b)), key1, key2 and the way of space cycle bit shift is only one correct, unscrambling result as shown in Fig. 7.

It can be seen from Fig. 7, even if the scrambling method is open, and only one secret-key is correct, image also can’t be recovered.

B. Histogram Analysis

Histogram reflects image statistical distribution, and usually is used for statistics analysis attack. The histograms of original image and its scrambled image as shown in Fig. 8, compare them that we can see great differences.

From Fig. 8, the histogram of the scrambled image is evenly distributed, completely changed the statistical properties of the original image. So it can hide the statistical distribution of the original image and increases the difficulty of unscrambling.
C. Correlation Analysis of Adjacent Pixels

In general, there has strong correlation between two adjacent pixels in an image. Thus scrambling algorithms should have strong de-correlation ability to destroy such correlation.

To test the correlation between two adjacent pixels in an image, the following procedure is performed. First, select 3000 pairs of two adjacent pixels in horizontal, vertical and diagonal directions randomly from an image. Then, calculate the correlation coefficients of each pair by using the formula [12]:

\[
    r_{xy} = \frac{\text{Cov}(x, y)}{\sqrt{D(x)} \cdot \sqrt{D(y)}}
\]

\[
    E(x) = \frac{1}{k} \sum_{i=1}^{k} x_i
\]

\[
    D(x) = \frac{1}{k} \sum_{i=1}^{k} (x_i - E(x))^2
\]

\[
    \text{Cov}(x, y) = \frac{1}{k} \sum_{i=1}^{k} (x_i - E(x))(y_i - E(y))
\]

, where \(x\) and \(y\) are grey-scale values of two adjacent pixels in the image. Fig. 9 shows the correlation distribution of two horizontally adjacent pixels in the original gray image (Fig. 4 (a)), its scrambled gray image (Fig. 4 (b)), R component of the original color image (Fig. 6 (a)) and R component of its scrambled image (Fig. 6 (b)).

![Figure 9. Correlations of two horizontally adjacent pixels: (a) original gray image (Fig. 4(a)) correlation, (b) scrambling gray image (Fig. 4(b)) correlation, (c) R component of original color image (Fig. 6(a)) correlation, (d) R component of scrambling color image (Fig. 6(b)) correlation](image)

It can be seen from Fig. 9 that the correlation of adjacent pixels in the original image is very strong, and adjacent pixels of scrambled image are completely distributed to the entire image. The results are the same to vertical and diagonal directions. Correlation coefficients of adjacent pixels in horizontal, vertical and diagonal directions were calculated, which were shown in Table I.

<table>
<thead>
<tr>
<th>Correlation Calculation Based on</th>
<th>Original gray image (Fig.4(a))</th>
<th>Scrambled gray image (Fig.4(b))</th>
<th>R component of original color image (Fig. 6(a))</th>
<th>R component of scrambled color image (Fig. 6(b))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal direction</td>
<td>0.9380</td>
<td>0.0147</td>
<td>0.9600</td>
<td>0.0057</td>
</tr>
<tr>
<td>Vertical direction</td>
<td>0.9716</td>
<td>0.0112</td>
<td>0.9721</td>
<td>0.0142</td>
</tr>
<tr>
<td>Diagonal direction</td>
<td>0.9180</td>
<td>0.0109</td>
<td>0.9204</td>
<td>0.0185</td>
</tr>
</tbody>
</table>

D. Entropy Analysis

Entropy can measure the distribution of the image gray value. The more uniform distribution of the image gray value, the greater the information entropy, on the contrary, the smaller the information entropy. Entropy calculation expression is as follows:

\[
    H(x) = \sum_{i=1}^{n} p(x_i) \log_2 p(x_i)
\]

, where \(x\) is a random variable, that represents the image pixel values, \(p(x_i)\) is the occurrence probability of \(x_i\).

According to (12), we calculated entropy of the scrambled gray image (Fig. 4 (b)), that was 7.9967. The entropy of R, G and B components of the scrambled color image (Fig. 6 (b)) were 7.9986, 7.9981 and 7.9983. These values of entropy were all very close to theoretical limit of the 8-bits image. It shows that the probability of pixel values in the scrambled image is almost same.

E. Data Loss Attacks

Data loss attacks are common image attacks. These attacks are to verify the ability of the scrambled images for tolerating the distortions in the public media transmission channels. Consequently, the scrambling algorithm in the paper show great advantages in data loss attacks.

Fig. 10 gave an example of cutting attacks. We separately did some different cutting attacks on the scrambling gray image (Fig. 4 (b)). The reconstructed images shown in Fig. 10 were derived from these scrambled images with cutting attacks. These reconstructed images were visually acceptable since they include almost all visual information of the original image.
Figure 10. Different cutting attacks and reconstructed images: (a) image of 1/16 cut, (b) reconstructed image of (a), (c) image of multi-cut, (d) reconstructed image of (c), (e) image of center cut, (f) reconstructed image of (e), (g) image of 1/2 cut, (h) reconstructed image of (g).

These experimental results demonstrate that the scrambling algorithm has uniform scrambling effect.

F. Noise Attacks

There are many different noises in the public media transmission channels such as networks. Noise attacks show the ability of the scrambled images for enduring the noise attacks. This shows another advantage of the image scrambling algorithm. The experimental results in Fig. 11 show the performance of the scrambling algorithm in noise attacks.

We separately added some different noise attacks on the scrambling gray image (Fig. 4 (b)). The images were recovered from these scrambled images with noise. The recovered images were shown in Fig. 11.

There has one thing need to be noted, that is, to have a stronger ability against noise attacks, we had better do not exchange the high bit-plane value and the low bit-plane value in the SBPO. However, at this time the scrambling image uniformity is slightly worse.

Figure 11. Adding noise attacks and reconstructed images: (a) reconstructed image with 2% Salt & Pepper noise attack, (b) reconstructed image with 20% Salt & Pepper noise attack, (c) reconstructed image with 2% Gaussian noise attack, (d) reconstructed image with 20% Gaussian noise attack.

These recovered images contain almost all the visual information of the original image even though they contain noises. These experimental results demonstrate that the scrambling method show good performance in the presence of noise attacks. The scrambled images can be recovered when subjected to noisy environments.
VI. CONCLUSION

In this paper, an image scrambling algorithm based on SBPO and chaotic sequence combination was proposed. The proposed algorithm can shuffle the positions and change the gray values of image pixels simultaneously, also it can make up this deficiency which the low security of image scrambling using bit-exchange operation on single pixel or adjacent pixels to scramble digital image.

Experimental results demonstrate that the proposed algorithm successfully achieves image scrambling, showing effective hiding ability for image information with significant advantages:

- Easy to operate.
- Small computation burden.
- Strong adaptability. It is applicable for various types and sizes of image scrambling.
- Strong applicability. It possesses perfect confusion properties and it can resist the various attacks.

So our algorithm can be used on a digital image scrambling, and has some practical application value in image information hidden area.

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REFERENCES


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