Research Article

Image Blocking Encryption Algorithm Based on Laser Chaos Synchronization

Shu-Ying Wang,¹ Jian-Feng Zhao,² Xian-Feng Li,³ and Li-Tao Zhang⁴

¹Department of Nationalities, Huanghe Science and Technology College, Zhengzhou 450053, China

²Department of Information Engineering, Henan Polytechnic, Zhengzhou 450046, China

³College of Mathematics and Science, Lanzhou Jiaotong University, Lanzhou 730070, China

⁴Department of Mathematics and Physics, Zhengzhou Institute of Aeronautical Industry Management, Zhengzhou 450015, China

Correspondence should be addressed to Jian-Feng Zhao; zjfzwf@126.com

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In view of the digital image transmission security, based on laser chaos synchronization and Arnold cat map, a novel image encryption scheme is proposed. Based on pixel values of plain image a parameter is generated to influence the secret key. Sequences of the drive system and response system are pretreated by the same method and make image blocking encryption scheme for plain image. Finally, pixels position are scrambled by general Arnold transformation. In decryption process, the chaotic synchronization accuracy is fully considered and the relationship between the effect of synchronization and decryption is analyzed, which has characteristics of high precision, higher efficiency, simplicity, flexibility, and better controllability. The experimental results show that the encryption algorithm image has high security and good antijamming performance.

1. Introduction

With the rapid development of information transmission technology, electronic data interchange is an important way to communicate and exchange information. Multimedia information with secure communication problems urgently needs to be solved. Characteristics of chaotic sequence have natural advantages in cryptography. During the late 1980s, the British mathematician Matthews put forward the chaos into cryptography firstly [1]. As the traditional encryption technique DES cannot be directly used for image encryption, recently many special properties of chaotic maps are suitable to encrypt digital image and provide a new idea to select data security problem of multimedia information [2–7].

The laser chaos not only has complex phenomena of all dissipative systems, but also has excellent characteristics such as built-in self-test ability (BIST), pulse generation, closeness to the ideal model, and easiness of design compared with theory. Chaotic laser signal with inherent broad band, noise, and unpredictable characteristics greatly increased the

difficulty of optoelectronic reconnaissance and is an important technology of optical information security. The laser-based digital communication was put forward by Colet and Roy in 1994 [8] and became increasingly popular in recent years [9–11].

Synchronization is a basic characteristic of complex system and the phenomenon generally exists in natural ecosystem and artificial system such as biology, engineering, and machinery [12, 13]. Synchronization of chaotic systems and secure communication have become research hotspots of nonlinear system [14, 15]. With simple structure the linear feedback controller is easily implemented physically and has high practical value, but chaos synchronization is rarely applied in digital image encryption [16, 17].

This paper is organized as follows. In Section 2, linear feedback synchronization of Lorenz-Haken is introduced. In Section 3, based on chaos synchronization, a novel image encryption algorithm is proposed. In Section 4, numerical simulation is given to illustrate the effectiveness of the proposed algorithm. Finally, the paper concludes in Section 5.

FIGURE 1: Laser chaos.

2. Linear Feedback Synchronization of Lorenz-Haken Laser Chaos

The mathematical description of the Lorenz-Haken laser chaos [20] is

$$\begin{aligned}\dot{x} &= a(y - x), \\ \dot{y} &= bx - y - xz, \\ \dot{z} &= xy - cz,\end{aligned}\quad (1)$$

where $X = (x, y, z)^T$ is state vector of system (1) and a, b, c are system parameters assigned to $(a, b, c) = (1.4253, 50, 0.2775)$. Initial conditions are $(x_0, y_0, z_0) = (1, 0, 50)$ and time is $t \in [0, 100s]$.

In view of the boundary of chaotic attractor, there are positive numbers M_x, M_y , and M_z , and $|x| \leq M_x$, $|y| \leq M_y$, and $|z| \leq M_z$. Figure 1 shows the phase diagram of chaotic system and state variables which meet the range $-9 < x < 9$, $-21 < y < 21$, and $21 < z < 81$.

System (1) is used as the drive system, and the response system is defined as follows:

$$\begin{aligned}\dot{x}_1 &= a(y_1 - x_1) + u_1, \\ \dot{y}_1 &= bx_1 - y_1 - x_1z_1 + u_2, \\ \dot{z}_1 &= x_1y_1 - cz_1 + u_3.\end{aligned}\quad (2)$$

Suppose that error variables of the system are $e_1 = x - x_1$, $e_2 = y - y_1$, and $e_3 = z - z_1$. A linear feedback controller is selected as $u_i = -k_i e_i$, ($i = 1, 2, 3$).

Then we get the error system:

$$\begin{aligned}\dot{e}_1 &= (k_1 - a)e_1 + ae_2, \\ \dot{e}_2 &= be_1 + (k_2 - 1)e_2 + xz - x_1z_1, \\ \dot{e}_3 &= (k_3 - c)e_3 - xy + x_1y_1.\end{aligned}\quad (3)$$

The Lyapunov function is designed as $V = (1/2)(e_1^2 + e_2^2 + e_3^2)$; then tracking along system (3), we obtain its time derivative:

$$\begin{aligned}\dot{V} &= e_1\dot{e}_1 + e_2\dot{e}_2 + e_3\dot{e}_3 \\ &= (k_1 - a)e_1^2 + ae_1e_2 + be_1e_2 + (k_2 - 1)e_2^2 \\ &\quad + (k_3 + b)e_3^2 + (xz - x_1z_1)e_2 + (k_3 - c)e_3^2 \\ &\quad + (x_1y_1 - xy)e_3 \\ &= \left(k_1 - a + \frac{(a+b-z)^2 + y^2}{4}\right)e_1^2 + k_2e_2^2 \\ &\quad + (k_3 - c + 1)e_3^2 - \left(e_2 - \frac{a+b-z}{2}e_1\right)^2 \\ &\quad - \left(e_3 - \frac{y}{2}e_1\right)^2.\end{aligned}\quad (4)$$

To obtain the asymptotic stability of error system, that is to say, $\dot{V} \leq 0$, the following conditions need to be satisfied:

$$\begin{aligned}k_1 - a + \frac{(a+b-z)^2 + y^2}{4} &< 0, \\ k_2 &< 0, \\ k_3 - c + 1 &< 0.\end{aligned}\quad (5)$$

Sufficient conditions of the feedback gains k_1, k_2 , and k_3 are

$$\begin{aligned}k_1 &< a - \frac{(a+b)^2 + M_z^2 + M_y^2}{4}, \\ k_2 &< 0, \\ k_3 &< c - 1.\end{aligned}\quad (6)$$

FIGURE 2: The synchronization error curves between drive system and response system.

TABLE 1: Components of matrix B .

$m = 0$	$m = 1$	$m = 2$	$m = 3$
$B = \{B, x, y, z\}$	$B = \{B, z, x, y\}$	$B = \{B, y, z, x\}$	$B = \{B, x, z, y\}$

In numerical simulation experiment, the slave system is considered with the same parameters as the master system. Initial state variables of them are $(x(0), y(0), z(0)) = (1, 0, 30)$ and $(x(0), y(0), z(0)) = (1, 0, 30)$, respectively. Figure 2 presents the synchronization error curves between drive system and response system which approaches to zero gradually. Completely synchronization is achieved in five seconds by using macroscopic observation, but in fact there is a synchronization error. The enlargement of partial positions of error curve is shown in Figure 2(b).

3. Description of the Algorithm

The original image of size $L = M \times N$, where M and N denote numbers of row and column, respectively. By scanning line by line, the original image is rearranged into matrix P :

- (1) Parametric perturbation is defined by adopting formula $T = \text{mod}(\sum_{i=1}^L P(i), L)/(L-1)$. Parameters x_0, y_0, z_0, a, b, c , and r are selected as secret key; $\{x, y, z\}$ are obtained by every chaos iteration. Then $n_0 = 1000$ data points are abandoned and state variables are recombined. Let $m = \text{mod}(\text{abs}(x(n_0 : n_0 + L - 1) + y(n_0 : n_0 + L - 1) + z(n_0 : n_0 + L - 1)), 3)$, and extend zero matrix B in Table 1.

- (2) The sequence B is processed as follows:

$$K(i) = \text{mod}(\text{floor}(|B(i)| - \text{floor}(|B(i)|)) \times 10^{m_2}), 256), \quad (7)$$

where $m_2 \in \mathbb{Z}^+$, $1 \leq m_2 \leq 15$, and $i = 1, 2, \dots, L$. $|x|$ is absolute of x , and $\text{floor}(x)$ indicates down integral function. Obviously, $K(i) \in [0, 255]$ after modular arithmetic. In the paper positive integral $m_2 = 10$. Chaotic sequence B shown in Figure 3(a) is treated as K ; self-correlation of K is approximate to zero presented in Figure 3(b). Figure 3(c) displays the local amplification at longitudinal amplification, and most of data are concentrated in interval $[-0.002, 0.002]$. After preprocessing the randomness of chaotic sequence is improved distinctly, and sequence after treatment is more suitable in cryptography.

- (3) Exclusive OR operation and modular arithmetic are imposed to the plain image by using sequence K . The first pixel point is encrypted individually, and its encryption exerts effect on encryption of the second pixel. The pixels are encrypted alternately as follows:

$$\begin{aligned}
 C(2) &= [P(2) + K(2)] \text{ mod } 256 \\
 &\oplus [C(1) + K(L)] \text{ mod } 256 \\
 &\text{for } i = 3 : 2 : L
 \end{aligned}$$

FIGURE 3: Self-correlation of chaotic sequence before and after treatment.

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C(i)
= [P(i) + K(i)] mod 256
⊕ [C(i - 2) + K(i + L)] mod 256
end
for i = 4:2:L
C(i)
= [P(i) + K(i)] mod 256
⊕ [C(i - 2) + K(L - i)] mod 256
end

```

(8)

The encrypted pixel sequence $\{C(i)\}$ is transformed into matrix C of size $M \times N$ with reshape command.

- (4) In the process of scrambling, general Arnold transform is used to scramble image C and get scrambled

image D . RGB segments of color digital image are scrambled by general Arnold transform with different parameters.

For the given symmetric algorithm, decryption is the inverse operation of encryption, described as follows:

- (1) The final encrypted image D is inversely scrambled to get image C .
- (2) Chaotic sequences of response system are used to perform antisubstitution decryption operation; the calculation formula is as follows:

for $i = L: -2:3$

$$\begin{aligned}
 P(i) &= \text{mod}(C(i) \oplus \text{mod}(C(i - 2) \oplus K(i + L), 256), 256) \\
 &\quad \oplus K(i)
 \end{aligned}$$

(a) Plain image

(b) Histogram of (a)

(c) Encrypted image

(d) Histogram of (c)

(e) Plain image

(f) Histogram of (e)

(g) Encrypted image

(h) Histogram of (g)

FIGURE 4: Continued.

(i) Plain image

(j) Histogram of (i)

(k) Encrypted image

(l) Histogram of (k)

(m) Plain image

(n) Histogram of (m)

(o) Encrypted image

(p) Histogram of (o)

FIGURE 4: Continued.

FIGURE 4: The histograms of gray images with different sizes: (a) 220×220 ; (e) 256×256 ; (i) 512×512 ; (m) 1024×1024 ; and (q) 220×565 .

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end
for  $i = L : -2 : 4$ 
 $P(i)$ 
= mod ( $C(i) \oplus \text{mod}(C(i-2) \oplus K(L-i), 256), 256$ )
 $\oplus K(i)$ 
end
 $P(2)$ 
= mod ( $C(2) \oplus \text{mod}(C(1) \oplus K(L), 256), 256$ )
 $\oplus K(2)$ 
 $P(1)$ 
= mod ( $C(1) \oplus \text{mod}(C(L) \oplus K(L), 256), 256$ )
 $\oplus K(1)$ 
(9)

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In encryption algorithm, the digital image is stored as two-dimensional array, including pixel position scrambling and pixel value substitution. For an image of size $L = M \times N$, the total time complexity is $O(L)$ analyzed from the viewpoint of the “big-O notation.” Therefore, the efficiency of execution of the algorithm is ideal.

4. Numerical Simulation Results

To verify the effectiveness of the above algorithm, different types of images are carried out in experimentation by using MATLAB platform. Statistical histogram describes the distribution of image pixel. Under the ideal condition, histogram of encrypted image should be approximate to distribute evenly. Histograms of gray image, binary image, and color image and their encrypted images are proposed in Figures 4, 5, and 6, respectively. The eight fine horses gray image is a high resolution image with 370 dpi shown in Figure 4(q). We can see that the gray pixel values of the original image are concentrated in some values, but the histograms of different encrypted images are highly uniform.

4.1. Correlation Coefficients of Adjacent Pixels. Encryption algorithm is designed to reduce the correlation coefficients of adjacent pixels between plain image and encrypted image for resisting statistical attacks. Correlation coefficients of entire randomly selected 3000 pairs of horizontally, vertically, diagonally, and counterdiagonally adjacent pixels are determined. The correlation coefficients between two adjacent pixels of image are calculated by the following formula:

$$R_{xy} = \frac{\text{Conv}(x, y)}{\sqrt{D(x)}\sqrt{D(y)}}, \quad (10)$$

TABLE 2: Correlation coefficient of different plain images and cipher images.

Plain image	Horizontal	Vertical	Diagonal	Counterdiagonal
Gray girl (220 × 220)				
Plain image	0.972389	0.973428	0.946752	0.949101
Encrypted image	-2.342213×10^{-4}	1.178432×10^{-4}	4.210485×10^{-5}	-1.094222×10^{-4}
Gray Lena (256 × 256)				
Plain image	0.972953	0.970462	0.916925	0.938441
Encrypted image	-4.156125×10^{-4}	-2.552108×10^{-4}	-2.788174×10^{-5}	-4.829102×10^{-7}
Encrypted image [18]	0.000848277	0.00370914	-0.000189	
Encrypted image [19]	-0.0025	-0.0006	-0.0050	
Gray boat (512 × 512)				
Plain image	0.833645	0.941003	0.850811	0.833801
Encrypted image	-1.234977×10^{-4}	-2.219543×10^{-5}	3.325240×10^{-5}	7.915527×10^{-5}
Binary image (256 × 256)				
Plain image	0.986849	0.984293	0.965644	0.995392
Encrypted image	0.001569	1.869499×10^{-4}	-1.574389×10^{-4}	-1.099277×10^{-4}
Gray Elaine (1024 × 1024)				
Plain image	0.978254	0.966275	0.956931	0.955351
Encrypted image	8.903521×10^{-4}	1.018005×10^{-4}	6.933169×10^{-5}	7.263636×10^{-4}
Eight fine horses (220 × 565)				
Plain image	0.989809	0.983595	0.972294	0.972537
Encrypted image	5.485211×10^{-4}	1.546712×10^{-4}	-7.799651×10^{-5}	-8.218992×10^{-4}
Color baboon (512 × 512 × 3)				
Red				
Plain image	0.772788	0.583314	0.573087	0.509744
Encrypted image	3.495943×10^{-4}	8.087366×10^{-6}	2.572029×10^{-4}	-4.644542×10^{-5}
Green				
Plain image	0.807396	0.654726	0.650771	0.597617
Encrypted image	-5.508956×10^{-4}	-4.001587×10^{-4}	7.277112×10^{-5}	4.782903×10^{-4}
Blue				
Plain image	0.877479	0.790278	0.786803	0.761251
Encrypted image	-7.206039×10^{-5}	4.348691×10^{-4}	-8.564954×10^{-5}	-4.391072×10^{-4}

where

$$\begin{aligned}
 E(x) &= \frac{1}{N} \sum_{i=1}^N x_i, \\
 D(x) &= \frac{1}{N} \sum_{i=1}^N [x_i - E(x)]^2, \\
 \text{Conv}(x, y) &= \frac{1}{N} \sum_{i=1}^N [x_i - E(x)][y_i - E(y)],
 \end{aligned} \tag{11}$$

where x and y are pixel values of two adjacent pixels in the image.

Figure 7 and Table 2 display distribution of the randomly selected pairs of adjacent pixels in four directions of the original and encrypted image. If the correlation of the encrypted images is close to zero, then it informs good encryption quality. It is clear that the correlation coefficient of the proposed algorithm is smaller than that of other methods proposed in [18, 19].

4.2. Information Entropy. The concept information entropy was put forward by Shannon [21], which lays the foundation for information theory and digital communication. Information entropy is commonly used to express image texture features and measure the randomness. The entropy $H(x)$ is measured by the formula $H(x) = -\sum_{i=1}^n p(x_i) \log_2 p(x_i)$, where $p(x_i)$ denotes the probability of symbol x_i . In theory, the maximum entropy is $H_{\max} = -(1/256) \log_2 (1/256) \times 256 = 8$ for a gray image.

From Table 3, it is clear that our approach can encrypt a low entropy image to get higher entropy image which has random information content. The entropy of the encrypted image is actually closer to the maximum entropy than the plain image. The gray distribution of the encrypted image is more uniform, and its security is improved greatly. Obviously the encryption algorithm has better ability to resist statistical attack.

4.3. Decryption Effect. In numerical simulation, encrypted gray Lena image is decrypted by abandoning 0 points, 1000 points, 3000 points, 5000 points, and 7000 points, and

FIGURE 5: The binary image with size of 256×256 .

TABLE 3: The entropy of plain image and its corresponding encrypted image.

	Gray images						Color baboon		
	Girl	Lena	Boat	Binary	Elaine	Eight fine horses	Red	Green	Blue
Plain image	7.7256	7.5769	7.1951	1.0060	7.5030	6.9958	7.7532	7.4642	7.7722
Encrypted image	7.9887	7.9898	7.9910	7.9916	7.9915	7.9905	7.9916	7.9917	7.9915

their effects are represented in Figure 8. When the complete synchronization has not yet been achieved, the decryption effect is better with more abandoned points unsynchronized. Subtle difference between plain image and decrypted image cannot be observed subjectively. To avoid uncertainty of subjective evaluation, subjective evaluation is necessary for recovery performance. Common objective indexes are Mean Square Error (MSE) and Peak Signal to Noise Ratio (PSNR) defined as follows:

$$\text{MSE} = \frac{1}{M \cdot N} \sum_{i=1}^M \sum_{j=1}^N \|P(i, j) - I(i, j)\|^2, \quad (12)$$

$$\text{PSNR} = 10 \cdot \log_{10} \left(\frac{\text{MAX}_I^2}{\text{MSE}} \right).$$

MSE is Mean Square Error between plain image P and processed image I ; MAX_I indicates that the maximum number of image colors is 255 with 8 bits per sample. PSNR is essentially identical to MSE, which is the logarithmic representation of MSE. However, MSE has poor correlation with subjective evaluation, so PSNR is usually used as evaluation index. PSNR is inversely proportional to effect of image encryption. When PSNR is more than 28 dB, the decrypted image has better quality. In fact it cannot even distinguish difference with the naked eye when PSNR is up to [35 dB, 40 dB]. After abandoning 0 points, 1000 points, 3000 points, 5000 points, and 7000 points, MSE and PSNR of decrypted gray are listed in Table 4. Comparing with the encrypted Lena, abandoning 7000 points has minimal distortion.

FIGURE 6: The color parrot image: (a) the plain image and histograms of its RGB segments and (b) the encrypted image and histograms of its RGB segments.

FIGURE 7: Correlation distribution of adjacent pixels: (a) plain Lena image and (b) encrypted Lena image.

4.4. Anti-Interference Attack. During transmission and other treatments, it is subjected to interferences and attacks. The anti-interference attack is an important indicator of testing the quality of the decryption algorithm. Encrypted images with 25% occlusion and 50% occlusion are represented in Figures 9(a) and 9(b); their decrypted images are shown in Figures 9(d) and 9(e), respectively. It is clear that the occlusion parts are diffused uniformly to the whole image;

therefore algorithm of the paper has strong capability against cropping operation.

If the encrypted image is added, salt-and-pepper noise is seen with noise density 0.002, when using the same key to restore the attacked image; the decrypted images are shown in Figure 9(f). It is clear that the encryption algorithm for salt-and-pepper noise attack has good ability to resist interference attack.

FIGURE 8: Decryption images of Lena with different dispose points.

TABLE 4: MSE and PSNR of different encrypted images under different reject points.

Value	Reject points					Encrypted Lena
	0	1000	3000	5000	7000	
MSE	733.9676	648.8245	372.7224	62.9877	0.1208	9009.3366
PSNR	19.4740	20.0094	22.4169	30.1382	57.3078	8.5838

5. Conclusion

Linear feedback controller is designed to synchronize the laser chaos and has higher precision. Steady-state error of synchronization reached 10^{-14} . Based on synchronization a novel encryption algorithm is designed. Numerical simulation results show that the given algorithm has sufficiently large key space, highly sensitive keys, better pixel distribution characteristics, and good performance against ciphertext-only attack, differential attack, chosen plaintext attack, and statistical attack. The algorithm can be widely used in secure communication of multimedia data. Linear feedback controller has convenient operation and strong applicability and is suitable for industrial application. The synchronization of chaotic laser systems is applied in image encryption

transmission and achieved good results. The algorithm can realize complete encryption in sender and lossless decryption in the receiver, so as to achieve digital image encryption transmission function.

Competing Interests

The authors declare that they have no competing interests.

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FIGURE 9: Encrypted image with (a) 25% occlusion, (b) 50% occlusion, and (c) salt-and-pepper noise; (d) decrypted image from (a), (e) decrypted image from (b), and (f) decrypted image from (c).

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