Digital Signal Processing 116 (2021) 103103

Contents lists available at ScienceDirect

Digital Signal Processing

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# Cancellable face recognition based on fractional-order Lorenz chaotic system and Haar wavelet fusion

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ARTICLE INFO

*Article history:*
Available online 28 May 2021

*Keywords:*
Cancellable biometrics
FO Lorenz chaotic systems
Random projection (RP)
Homomorphic transform
AROC

ABSTRACT

Cancellable biometrics is the art of generating distorted or encrypted templates of original biometric templates. The evolution of cancellable biometrics is attributed to the advanced hacking technologies that can capture the original stored biometrics from databases. One of the solutions for this problem is to store cancellable biometric templates in the database rather than the original ones. This paper presents a cancellable face recognition scheme that is based on face image encryption with Fractional-Order (FO) Lorenz chaotic system. The basic idea is to generate user-specific random keys to be XORed with the red, green, and blue components of color face images. These keys are generated from the fractional-order Lorenz chaotic system. In addition, some post-processing is implemented on the encrypted color components of the face images with rotation and transposition of matrices. Finally, a wavelet fusion process is applied on these encrypted and processed face image components. The reason behind the utilization of wavelet fusion is to generate a single cancellable template for each color face image. Furthermore, wavelet fusion after post-processing of encrypted color components leads to a better degree of diffusion in the encrypted face templates. Actually, the encryption with the proposed algorithm is not full encryption, but it is appropriate for cancellable biometric applications. Moreover, the proposed scheme is secure due to the power of fractional-order Lorenz chaotic system that is very sensitive to initial conditions selected by the user. In addition, the post-processing incorporated with wavelet fusion is a non-invertible process. The validation of the proposed scheme is performed with experiments on FERET, LFW, and ORL databases. Evaluation metrics including Equal Error Rate (EER), Area under the Receiver Operating Characteristic (AROC) curve are utilized in the proposed scheme. Numerical values reveal EER levels close to zero and AROC values of 100% at low and mild noise levels.

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## 1. Introduction

Chaos [1] has very interesting phenomena. It has gained a lot of attention, and it is becoming extremely important because of its applications in several real-world fields such as electronic systems [2], machine systems [3], mathematics [4], signal generators, biology [5], robotics, synchronization, random number generators, communication security [6], image processing [7] and so on. Chaos can originate from nonlinear dynamic systems. There are several types of chaotic dynamic systems. The Chua's circuit [8] is the simplest electronic circuit intentionally designed to exhibit nonlinear dynamic phenomena such as bifurcation and chaos. Lorenz system [9], Rossler system [10], Chen system [11], Lü system [12], Newton-Leipnik system [13], Arneodo system [14], Borah system [15], Lotka-Volterra System [16], Heart shape [17] Sprott [18] are examples of chaotic systems.

Fractional calculus [19] is the branch of mathematical analysis, which deals with applications of integral and differential operators

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https://doi.org/10.1016/j.dsp.2021.103103
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of non-integer order. The word fractional is a mistake, because the order can be real or complex. Over the past three decades, the topic of fractional calculus and its applications have gained much attention and publicity, mainly due to applications in several fields of science, physics, control systems, robotics, chaos, mechanical engineering, electromagnetics, signal processing, chemical mixing, bioengineering, electrical engineering and so on.

In recent years, the move towards the utilization of biometrics in security systems has captured the interest of researchers. The reason behind this move is to increase the security of access and identification systems compared to the systems that depend on traditional passwords. Nowadays, biometric authentication systems are widely used for personal authentication in a wide range of applications such as banks, airports, companies, institutions, public communication networks and forensic applications. Biometrics such as face, iris, fingerprint, and palm print always accompany the person without the need to remember any thing.

Unfortunately, there is a need to store the biometrics in databases, and hence they may be subject to attacks. Therefore, the utilization of traditional biometric systems becomes infeasible due to the advances of hacking mechanisms. This leads to the evolution of cancellable biometric ideas. Cancellable biometrics can be generated with non-invertible geometric transforms or encryption algorithms [20]. Non-invertible transforms can be performed with non-linear and non-periodic functions. These functions are used to transform indices of the face images with irregular methods to new indices. This induces geometric distortion of the face images. Unfortunately, this strategy does not hide the details of the face images. It induces some distortion for the automatic classification techniques that extract indices first. In [21], the authors presented an iris recognition scheme based on chaotic systems using Logistic map and a modified Logistic map, which produce random kernels that are convolved with the feature vectors extracted from the iris images to produce the encrypted templates. These templates are sensitive to initial conditions. The main limitation of this scheme is that the ERR is equal to 1.17%.

One of the encryption-based cancellable face recognition schemes [22] depends on the Minimum Average Correlation Energy (MACE) filter. Its basic idea is to use a random kernel generated with a certain key. This kernel is convolved with a group of face images and the results are merged together to generate the MACE filter during the training phase. During the testing phase, a new subject image is encrypted through convolution with the random kernel to generate an encrypted face template. Correlation estimation based on the encrypted MACE filter is used as the basic tool for recognition. High correlation ensures correct recognition. The main limitation of this algorithm is the ability to use deconvolution techniques with high computational power for decryption. In addition, the environment of encryption and verification is assumed to be noise-free.

Furthermore, the authors of [23] presented another non-invertible transformation that can be used for generating cancellable biometric templates depending on Random Projection (RP). The RP is followed by Log-Gabor filters to introduce another level of transformation in both enrollment and authentication phases. This algorithm has low security. The attacker can obtain the original biometric by knowing both the random projection matrix and the per-processing transform. Bio-convolving [24] is another algorithm that is used to generate cancellable biometric templates based on the transformation of the original biometrics into one dimensional (1D) signals and the division of the signals into parts. Each part is convolved with a different filter to increase the security level. Hence, the resulting signals are combined to generate the encrypted biometric templates.

Teoh et al. [25] presented a cancellable face recognition system based on bio-hashing. It depends on performing a certain transform on the faces, and hence feature extraction as shown in Fig. 1. The extracted features at this stage are not protected enough. The protection of the feature vector is performed with an inner product strategy on a multi-channel basis. Random basis matrices are generated with certain tokens that are multiplied with the feature vectors. Hence, multiple versions of encrypted features are obtained. The binary sequence obtained from the decisions for different products is used as a bio-hash for the face. Bio-hashes are compared based on a distance metric. This algorithm is simple in implementation, but the high accuracy of recognition needs a large number of inner products, and hence long bio-hashes. Other trends have been presented for cancellable face recognition with deep learning techniques.

Abdellatef et al. [26] presented an approach for cancellable face recognition based on deep learning. Different CNNs are used to extract deep features from facial patterns. The different feature vectors are fused together with the Principal Component Analysis (PCA) algorithm. The obtained feature vectors are then encrypted with bio-convolving. Random kernels are convolved with the obtained feature vectors to get the cancellable face templates. The security of this approach depends on the length of the random kernel used. Moreover, its effect can be inverted with a deconvolution algorithm.

Abdellatef et al. [27] presented another cancellable face recognition system based on both deep features and hand-crafted features. Deep features are extracted with deep Convolutional Neural Networks (CNNs). On the other hand, hand-crafted features are extracted with traditional feature extraction algorithms. The size of hand-crafted features is large, and hence the authors used dimensionality reduction to match the size of hand-crafted features to those of deep features. Feature fusion and bio-convolving are used to generate the cancellable templates. This trend also depends on bio-convolving leading to a limited performance. Abdellatef et al. [26] presented another approach based on deep learning to work on different facial regions. Deep features from different regions are generated and fused. Finally, bio-convolving is used for encryption. This approach also suffers from the weaknesses of bio-convolving.

Algarni et al. [28] developed a new trend for cancellable biometric recognition that depends on matrix rotation and discrete transforms. The basic idea of this trend is to use discrete transforms due to their ability to generate new templates with some sort of diffusion. Unfortunately, discrete transforms only are invertible. To avoid the ability of recovering the original biometric templates, matrix rotation is also exploited. A single matrix rotation is also invertible. That is why a bank of rotations is implemented. Several rotations are performed in the transform domain or prior to the transformation process. The rotated versions are added to eliminate the ability to recover the original templates. The simulation results in this paper proved the feasibility of this trend and revealed recognition results with EER down to 0.0023 and AROC values up to 99.8%. The best combination using this trend is that of Fractional Fourier Transform (FRFT) with a bank of rotations.

Optical encryption techniques can be exploited to secure biometric templates through the acquisition process. For example, the Double Random Phase Encoding (DRPE) can be implemented with two lenses in the so-called 4f system. Random phase masks are used to implement the DRPE. Soliman et al. [29] suggested the utilization of the DRPE to generate cancellable biometric templates with the help of the Scale-Invariant Feature Transform (SIFT) for feature extraction. The SIFT features are encrypted with DRPE either by implementing FFT or FRFT. The authors investigated their strategy on face and iris images and achieved EERs down to 0.63 and AROC values up to 0.9984.

Lamiaa et al. [30] investigated the utilization of 3D jigsaw transform for encryption of biometric templates. This transform is ap-

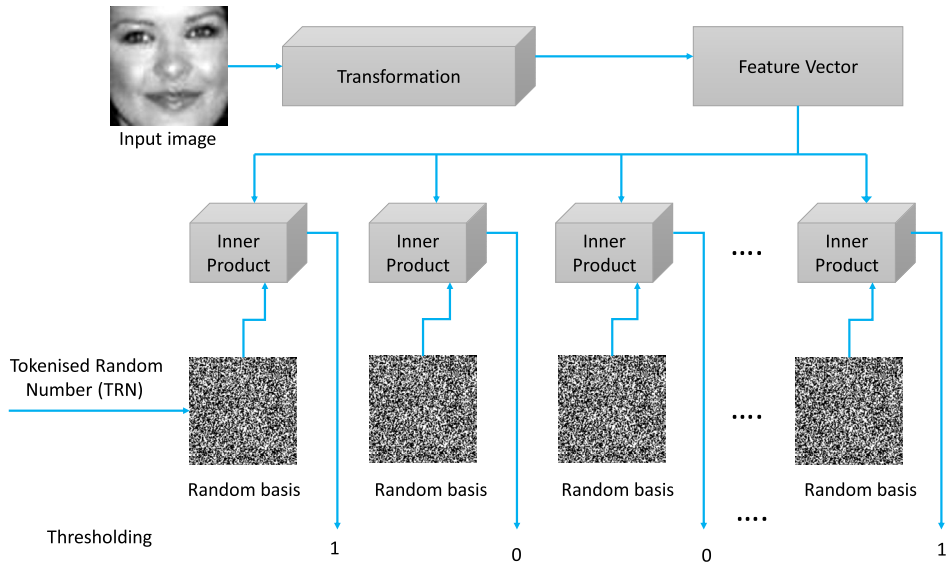



**Fig. 1.** Block diagram of bio-hashing.

plied with FRFT with different orders to add more degrees of freedom to the encryption process. The authors investigated this approach on face databases. It gives higher AROC values compared with those of other conventional approaches. The AROC values are up to 0.9997 and the EER values are down to $9.3997 \times 10^{-15}$.

Algarni et al. [31] presented two frameworks for cancellable biometrics that depend on pre-processing and encryption with RP after certain transformations. The first framework depends on intuitionistic fuzzy processing to modify the dynamic range of images. Hence, the encryption after that becomes non-invertible. Homomorphic transform is applied to decompose the image into illumination and reflectance that contains all details of the image, and hence it is encrypted with RP to generate the cancellable face template.

Liu et al. [32] presented a chaotic system that can be used for medical image encryption based on nonlinearity of a hyperbolic sin map. This chaotic system supports a large key space, because it has 6 control parameters and 4 initial conditions. The large key space gives better encryption results and strength against attacks. Hou et al. [33] presented a switching fractional order chaotic system that can be applied in image encryption based on XOR operation. From the fractional order Chen chaotic system, two subsystems can be generated. Hence, we have three systems that can produce large key sequences. Some of these key sequences are XORed with image pixel values to generate the encrypted image. To obtain the decrypted image, we apply the same operations with the same key sequences.

Liu et al. [34] presented a communication scheme based on fractional complex chaotic systems and fractional difference function synchronization to enhance the security of communication. Himeur et al. [35] presented a scheme to encrypt video watermark information based on a chaotic system in order to achieve a high degree of protection and simplicity of copyright information. Hua et al. [36] presented a nonlinear cosine transform to generate new chaotic maps that can be utilized in image encryption. Kaheni et al. [37] presented an encryption scheme for Wireless Sensor Network (WSN) applications. The message signal is encoded using a chaotic masking method and a type of fuzzy processing for enhancing the protection and preventing intrusion into WSNs at the transmitter side. At the receiver side, the message signal is decoded by the same scheme.

The proposed scheme in this paper depends on the utilization of FO chaotic systems with wavelet fusion using maximum fusion rule to generate cancellable biometric templates. The reason of utilization of the maximum fusion rule is to eliminate the ability of reconstruction of any channel component. The rest of this paper is organized as follows. Cancellable face recognition based on the homomorphic transform is presented in Section 2. Section 3 presents the cancellable face recognition scheme based on intuitionistic fuzzy. The proposed cancellable face recognition scheme based on FO Lorenz chaotic system is presented in Section 4. Dataset description and evaluation metrics are presented in Section 5. Also, section 5 presents the simulation results. Finally, Section 6 gives the concluding remarks.

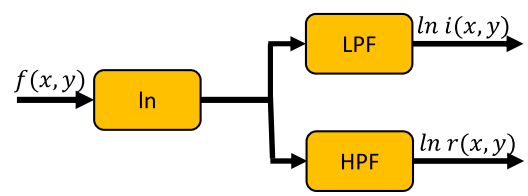



**Fig. 2.** Homomorphic decomposition of an image.

## 2. Homomorphic cancellable face recognition

In general, an image is a set of light quanta reflected from objects, meaning that any image $f(x, y)$ can be represented with two separate components: one representing the light falling on the objects and the other representing the light reflected from the objects. These components are called the illumination component and the reflectance component, and they are denoted as $i(x, y)$ and $r(x, y)$, respectively [38]. Thus, an image can be decomposed as illustrated in Fig. 2.

$$f(x, y) = i(x, y).r(x, y) \tag{1}$$

Generally, the light falling over the scene is almost constant. Changes only take place in the image reflectance component. This component can be separated based on a logarithmic operation and a High-Pass Filter (HPF) as depicted in Fig. 2.

$$\ln(f(x, y)) = \ln(i(x, y)) + \ln(r(x, y)) \tag{2}$$

One of the techniques used for image and feature encryption is the RP [39]. In other words, a random matrix is multiplied with the feature vector or lexicographically-ordered image component

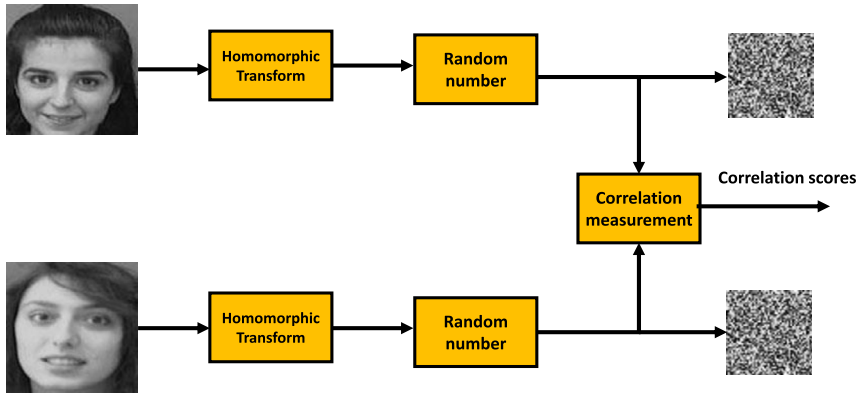



**Fig. 3.** Cancellable face recognition with homomorphic transform and RP.

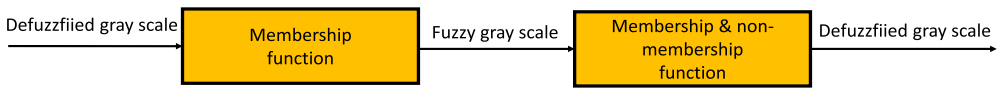



**Fig. 4.** Block diagram of Intuitionistic Fuzzy process in images.

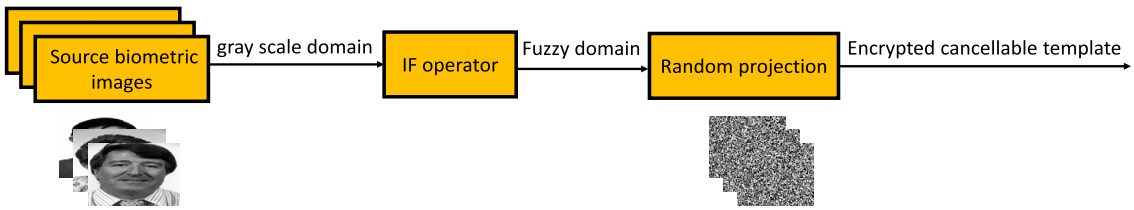



**Fig. 5.** Cancellable face recognitions based on IFL.

to obtain the encrypted pattern from the original biometric template. In [40], the reflectance component of the original biometric $\mathbf{X}_{d\times 1}$ is multiplied by a random matrix $\mathbf{A}_{Q\times d}$. The output of the RP process is represented as follows:

$$\mathbf{Y}_{Q\times 1} = \mathbf{A}_{Q\times d}.\mathbf{X}_{d\times 1}, \tag{3}$$

where $Q \times d$ and $d \times 1$ are the dimensions of the random matrix, and the original lexicographically-ordered reflectance component, respectively. The RP is popular due to its simplicity of implementation and its ability to preserve the distances between the encrypted biometric templates compared to the distances between the original ones. It is applied on the reflectance components in the scheme presented in [31], to obtain the cancellable templates. The illumination component is eliminated at all, and only information related to the reflectance component is kept. This process eliminates any redundancy in the template generation process (see Fig. 3).

## 3. Intuitionistic-fuzzy-based cancellable face recognition

Intuitionistic fuzzy processing is a common method used in several image processing techniques during the pre-processing phase [41]. Generally, the reason behind the utilization of intuitionistic fuzzy is to generate membership and non-membership degrees for every value in the biometric template.

$$\mu_A(p) = \frac{p - p_{min}}{p_{max} - p_{min}}, \tag{4}$$

where $p$ is the gray level of the original image $A$, $p_{min}$ and $p_{max}$ are the minimum and maximum gray levels in the images, respectively. The biometric source image in the form of an Intuitionistic Fuzzy Logic (IFL) image can be interpreted as:

$$A_{ifs} = \{< p, \mu_A(p,\lambda), v_A(p,\lambda) >| \; p \in 0, \ldots\ldots, l-1\} \tag{5}$$

where $\mu_A$ is the membership degree of pixel $p$ and $v_A$ is the non-membership degree of pixel $p$. In addition, Atanassov proposed a method of reconstruction to transform the IFL image into the gray domain as depicted in Eqns. (6), (7) [42].

$$p' = (l-1)\mu_{D(ifs)}(p) \tag{6}$$

$$\mu_{D(ifs)}(p) = \alpha + (1-\alpha)\mu_A(p;\lambda) - \alpha v_A(p;\lambda) \tag{7}$$

where $p$ and $p'$ are the initial and final intensity levels of the image, respectively and $\alpha$ is a constant value selected in the range $[0, 1]$. The IFL method [43] can be described in the form shown in Fig. 4, which illustrates the step of decorrelation for the image pixels prior to the next step of encryption. Fig. 5 illustrates a cancellable face recognition system based on IFL.

## 4. The proposed cancellable face recognition scheme

The proposed scheme depends on the encryption of face templates based on FO Lorenz chaotic system [44], [45]. The color face image is decomposed into three components: R, G, and B. Each component is processed separately as illustrated in Fig. 6. In this section, we firstly present the mathematical formulation of the FO calculus that will be adopted in the proposed system for biometric encryption. The FO calculus is a generalization of integration and differentiation to a non-integer-order fundamental operator ${}_fD_g^r$, where $f$ and $g$ are the limits of the operation and $r \in R$. For representation of the Lorenz chaotic system, at first, we present some definitions that are used to solve the derivative equations of the chaotic system. The three most commonly used definitions are the Riemann-Liouville, the Caputo and Grunwald-Letnikov. In this pa-

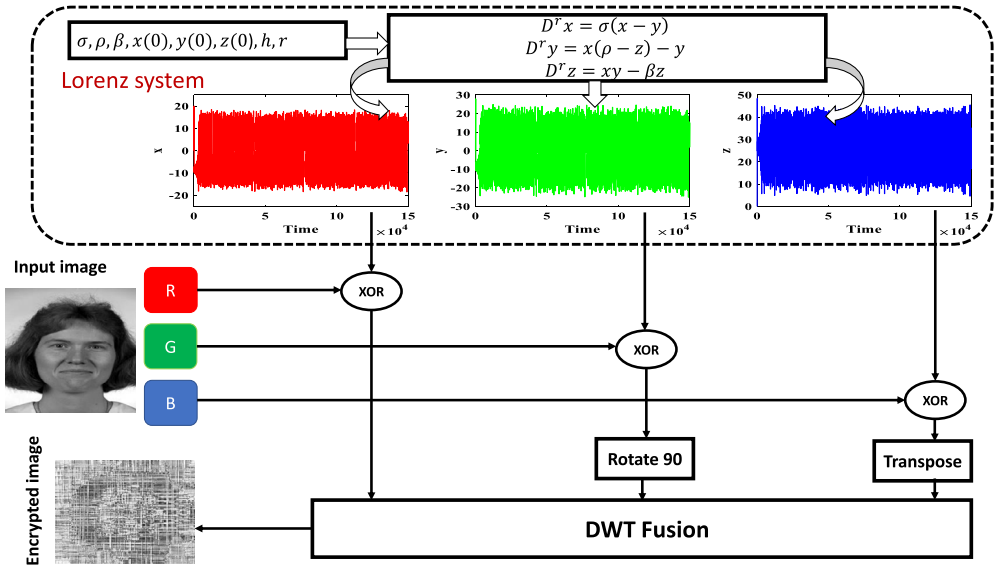



**Fig. 6.** Block diagram of image encryption based on FO Lorenz chaotic system.

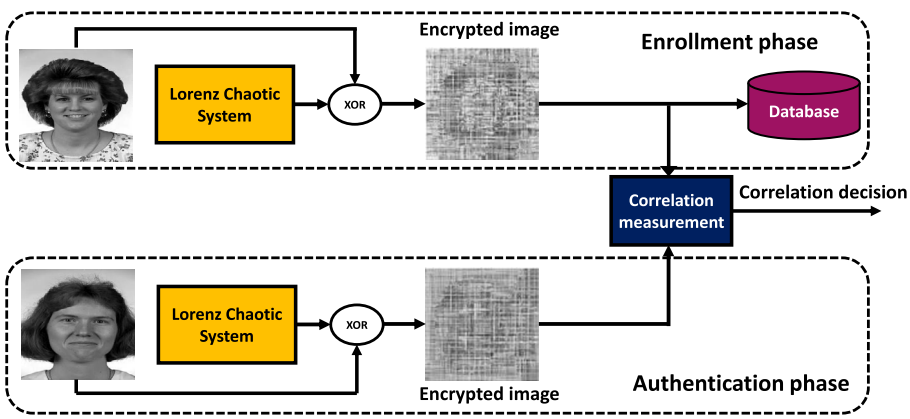



**Fig. 7.** The proposed FO Lorenz chaotic system applied for cancellable face recognition.

per, we adopt Grunwald-Letnikov to get the approximation of the FO derivative solution of the chaotic system [46], [47].

The Grunwald-Letnikov definition of fractional order $r$, where $m-1<r<m$ of function $v(t)$, is given as follows:

$$D_t^r f(t) = \frac{1}{h^r}\sum_{i=1}^{L} w_j^{(r)} f(t-ih),\ \ w_0^{(r)} = 1, \tag{8}$$

$$w_i^{(r)} = \left(1 - \frac{1+r}{i}\right) c|_{i-1}^{r},$$

$$w_0^{(r)} = 1,\ w_i^{(r)} = \left(1 - \frac{1+r}{i}\right) c|_{i-1}^{r}, \tag{9}$$

where $i = 1, 2, 3, \cdots$, $w_j^{(r)}$ are the binomial coefficients, and the memory length is donated by $L$, which depends on the behavior of the coefficients depicted in Eqn. (9). The stability theory of FO systems is quite different from that of the integer-order ones. This leads to the following definitions and legends.

Consider the general FO chaotic system of $N$-dimensions depicted in Eqn. (10). The equilibrium points of an FO differential system is obtained by setting the equation $f(Y) = 0$, where $D^r Y = (D^r y_1, D^r y_2, D^r y_3, \ldots, D^r y_n)^T$, $Y = (y_1, y_2, y_3, \ldots, y_n)^T \in R^n$.

$$D^r(Y) = f(Y). \tag{10}$$

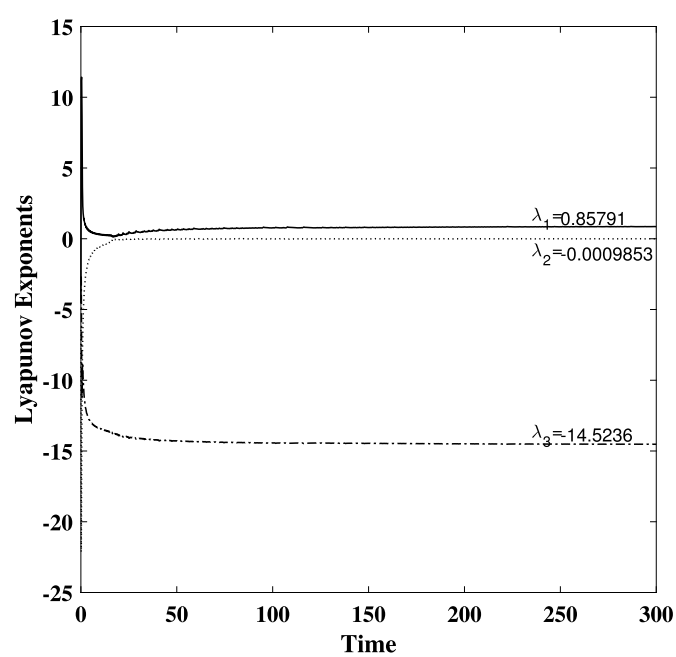
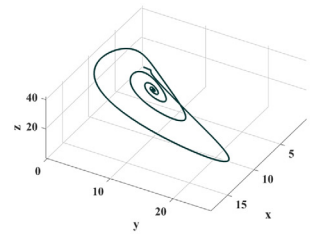
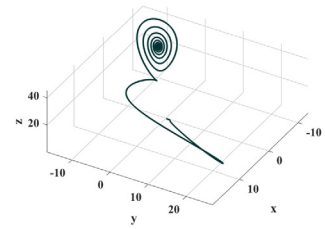
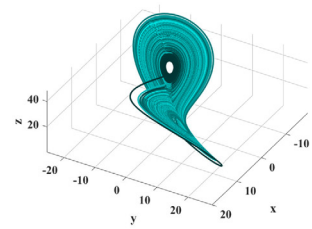
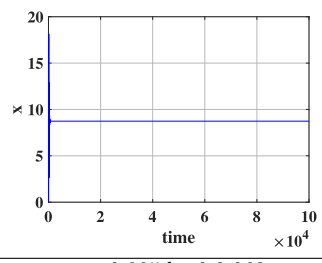
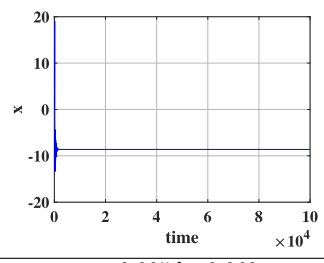
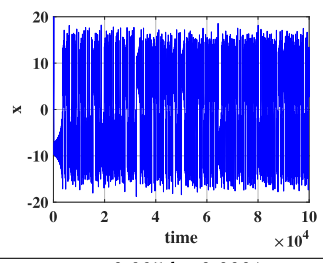
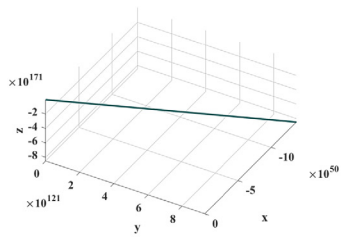
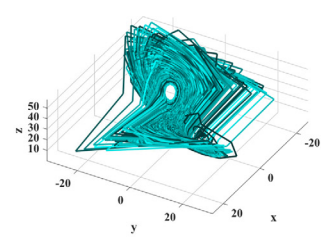
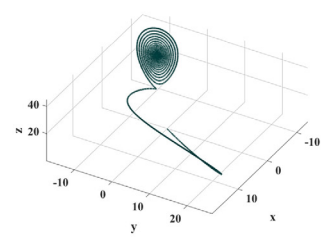
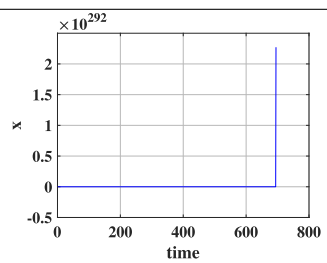
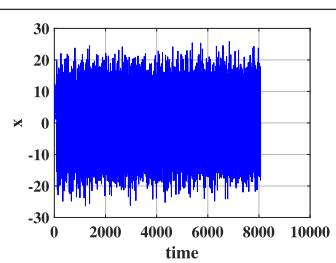
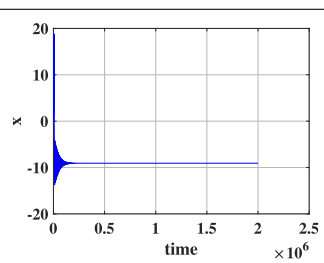



**Fig. 8.** Lyapunov exponent.

**Table 1**
Chaotic system based on step size ($h$) and fractional-order ($q$).

| | q=0.9,h=0.005 | q=0.95,h=0.005 | q=0.995,h=0.005 |
|---|---|---|---|
| Attractor |  |  |  |
| Phase portrait |  |  |  |
| | q=0.995,h=0.0.063 | q=0.995,h=0.062 | q=0.995,h=0.0001 |
| Attractor |  |  |  |
| Phase portrait |  |  |  |

The following legend is presented to determine the presence of the equilibrium point $O$ of index 2.

**Legend**. Considering $O$ as an equilibrium point of the system of Eqn. (10) and $\lambda_i$ as the eigenvalues of the Jacobian matrix $J$ at $O$ [48], [49].

If and only if:

1- $\sum_{i=0}^{n} \lambda_i < 0$,

2- Jacobian matrix has one of the eigenvalues less than zero and the others are complex conjugates,

3- $|\arg(\lambda_i(J))| < r\pi/2, i = 1, 2, 3$.

Then, the equilibrium point $O$ is named the saddle point of index 2. Generally, the equilibrium point with index 2 plays a vital role to produce an attractor, and the FO system can be chaotic if the FO satisfies the following condition

$$r > arg(\lambda) = \frac{2}{\pi} arctan \frac{|Im(\lambda)|}{|Re(\lambda)|}, \tag{11}$$

where $Re(\lambda)$ and $Im((\lambda)$ stands for the real and imaginary parts of $\lambda$, respectively. The equilibrium point $O$ is named saddle point of index 1, if and only if:

1- $\sum_{i=0}^{n} \lambda_i < 0$,

2- Jacobian matrix has one of the eigenvalues greater than zero and the other two are complex conjugates,

3- $|\arg(\lambda_i(J))| > r\pi/2, i = 1, 2, 3$.

### 4.1. Description of the proposed scheme

The proposed scheme depends on the Lorenz FO chaotic system to obtain the time series of $(x, y, z)$ that is employed in cancellable face recognition. This is described as follows:

$$\begin{cases} {}_0D_t^{r_1} x(t) &= \sigma(y(t) - x(t)), \\ {}_0D_t^{r_2} y(t) &= \rho x(t) - x(t)z(t) - y(t), \\ {}_0D_t^{r_3} z(t) &= x(t)y(t) - \beta z(t) \end{cases} \tag{12}$$

where $x, y$ and $z$ represent the state variables, $\sigma, \rho$ and $\beta$ are constants and $r_1 = r_2 = r_3$ are the fractional orders equal to 0.995. When $\sigma = 10$, $\rho = 28$ and $\beta = 8/3$, all state variables are equal to zero to get the equilibrium points. The eigenvalues of the Jacobian matrix in Eqn. (15) at the equilibrium point $(0, 0, 0)$ are $-22.8277, 11.8277 and -2.6677$. By employing the legend described above, the equilibrium point becomes a saddle point of index 1. This point connects between attractors. At the other

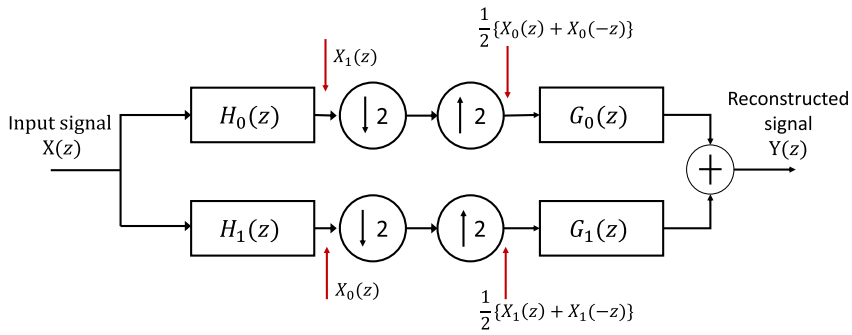



**Fig. 9.** Wavelet transform.

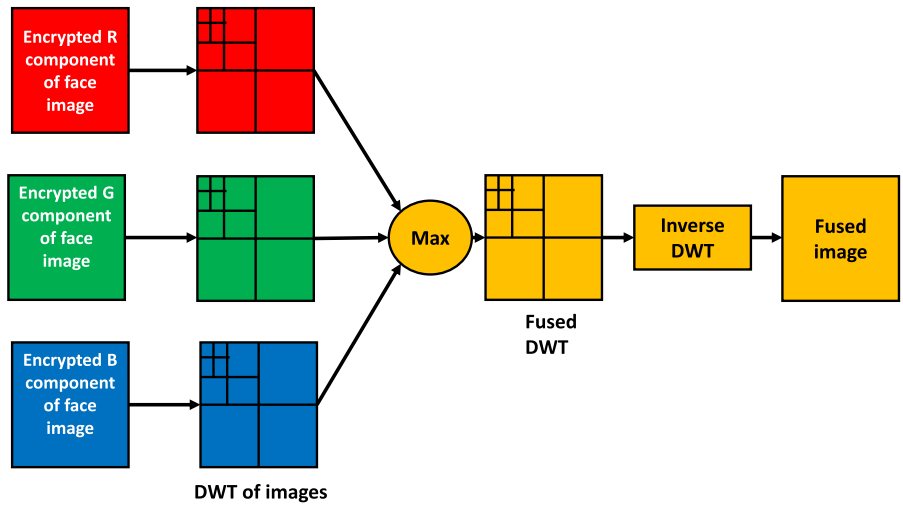



**Fig. 10.** Block diagram of the fusion process in the wavelet domain.

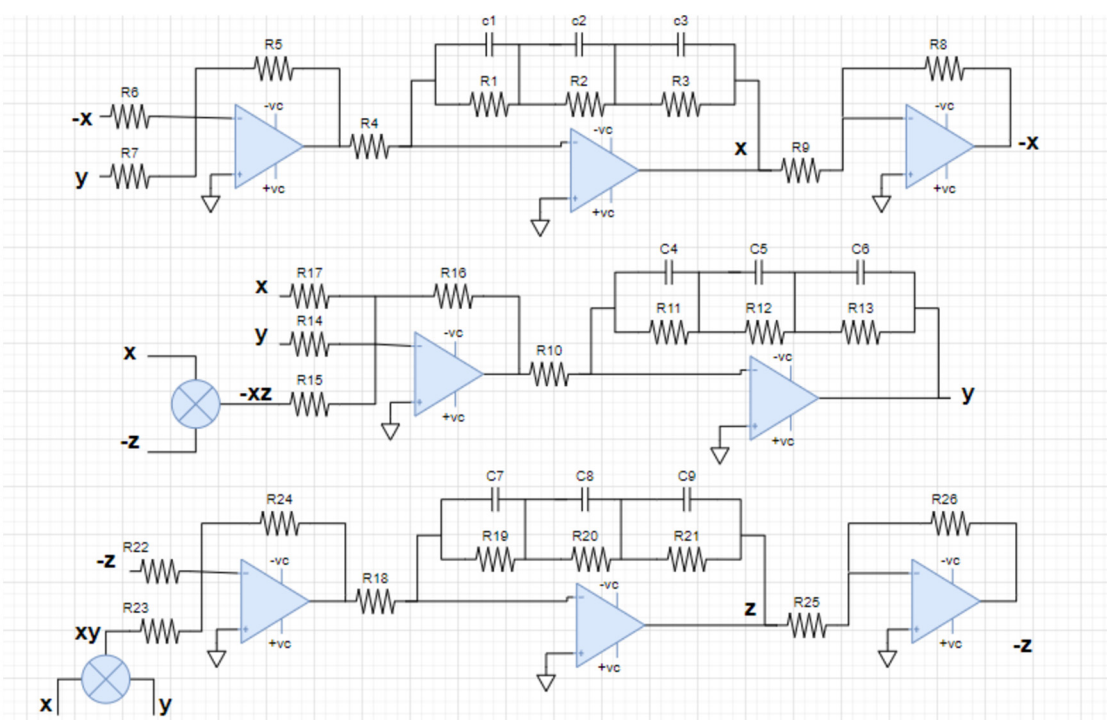



**Fig. 11.** Implementation of FO Lorenz chaotic system.

two equilibrium points $O$ $(\sqrt{\beta(\rho-1)}, \sqrt{\beta(\rho-1)}, \rho-1)$ and $O$ $(-\sqrt{\beta(\rho-1)}, -\sqrt{\beta(\rho-1)}, \rho-1)$, the eigenvalues of the characteristic roots of the Jacobian matrix in Eqn. (15) are $-13.8546$, $0.0940 \pm 0.1945i$, and $-13.8546$, $0.0940 \pm 10.1945i$. So, the two equilibrium points are saddle points of index 2.

Lyapunov exponents of FO Lorenz system with the selected initial conditions of $(0.1, 0.1, 0.1)$ are $0.85791, -0.0009853$ and $-14.5236$. At least, one positive Lyapunov exponent is required for the system to be chaotic as displayed in Fig. 8. Table 1 shows how different step sizes and FOs affect the system. The chaotic system is sensitive to initial conditions. The system may be chaotic or not depending on different step sizes and FOs [50] [51].

$$\begin{cases} {}_0D_t^{r_1}x(t) &= \sigma(y(t)-x(t)) = 0, \\ {}_0D_t^{r_2}y(t) &= \rho x(t) - x(t)z(t) - y(t) = 0, \\ {}_0D_t^{r_3}z(t) &= x(t)y(t) - \beta z(t) = 0 \end{cases} \tag{13}$$

$$J_(x^*, y^*, z^*) = \begin{pmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \frac{\partial f_1}{\partial z} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial y} & \frac{\partial f_2}{\partial z} \\ \frac{\partial f_3}{\partial x} & \frac{\partial f_3}{\partial y} & \frac{\partial f_3}{\partial z} \end{pmatrix} = \begin{pmatrix} -\sigma & \sigma & 0 \\ \rho - z & -1 & -x \\ y & x & -\beta \end{pmatrix}, \tag{14}$$

$$\begin{pmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda \end{pmatrix} - \begin{pmatrix} -\sigma & \sigma & 0 \\ \rho - z & -1 & -x \\ y & x & -\beta \end{pmatrix} = \begin{pmatrix} \lambda + \sigma & -\sigma & 0 \\ z - \rho & \lambda + 1 & x \\ -y & -x & \lambda + \beta \end{pmatrix} \tag{15}$$

As illustrated in Fig. 6, the three color components are separated using Matlab software. This figure shows the experimental encryption results of RGB images of size $227 \times 227 \times 3$ pixels. In this scenario, the XOR operation is performed between all state variables of the FO Lorenz chaotic system $(x, y, z)$ and all color image components $(R, G, B)$. In other words, $x$ component is XORed with $R$ components of face images. Similarly, both $x$ and $y$ state variables are XORed with $G$ and $B$ components, respectively, as shown in Fig. 12. To reduce the whole size of the encryption results of $R, G$ and $B$ components, some post-processing with rotation and transpose is implemented on the $G$ and $B$ encrypted components, respectively. Finally, wavelet fusion [52] is applied on the obtained results as depicted in Fig. 10. The objective of this process is twofold, to increase the security and reduce the size of the cancellable face template to be similar to that of each of the $R, G$ or $B$ components.

Both enrollment and authentication phases are illustrated in Fig. 7. In the enrollment phase, the obtained single encrypted biometric templates extracted from Fig. 6 can be stored in the database. In the testing phase (authentication phase), the same operations (XOR, rotation, transposition, wavelet fusion) are performed on new templates to obtain the encrypted versions of new subjects and compare with counterparts that are stored in the database to determine if the person has access to the system or not.

### 4.2. Wavelet fusion of encrypted components

The objective of the wavelet fusion step is to merge the encrypted color components that are obtained separately as shown in Fig. 10 into a single cancellable template for each face. Discrete Wavelet Transform (DWT) is one of the most famous mathematical tools. It is employed in many applications of image processing like image fusion, compression and restoration. Implementation of the DWT depends on a tree of filters. The DWT depends on the design of the filters $H_0, H_1, G_0$ and $G_1$. Moreover, the signal can be transformed into two components: Low-Pass (LP) and High-Pass (HP) in the time domain. Hence, the wavelet transform is also called time-frequency analysis.

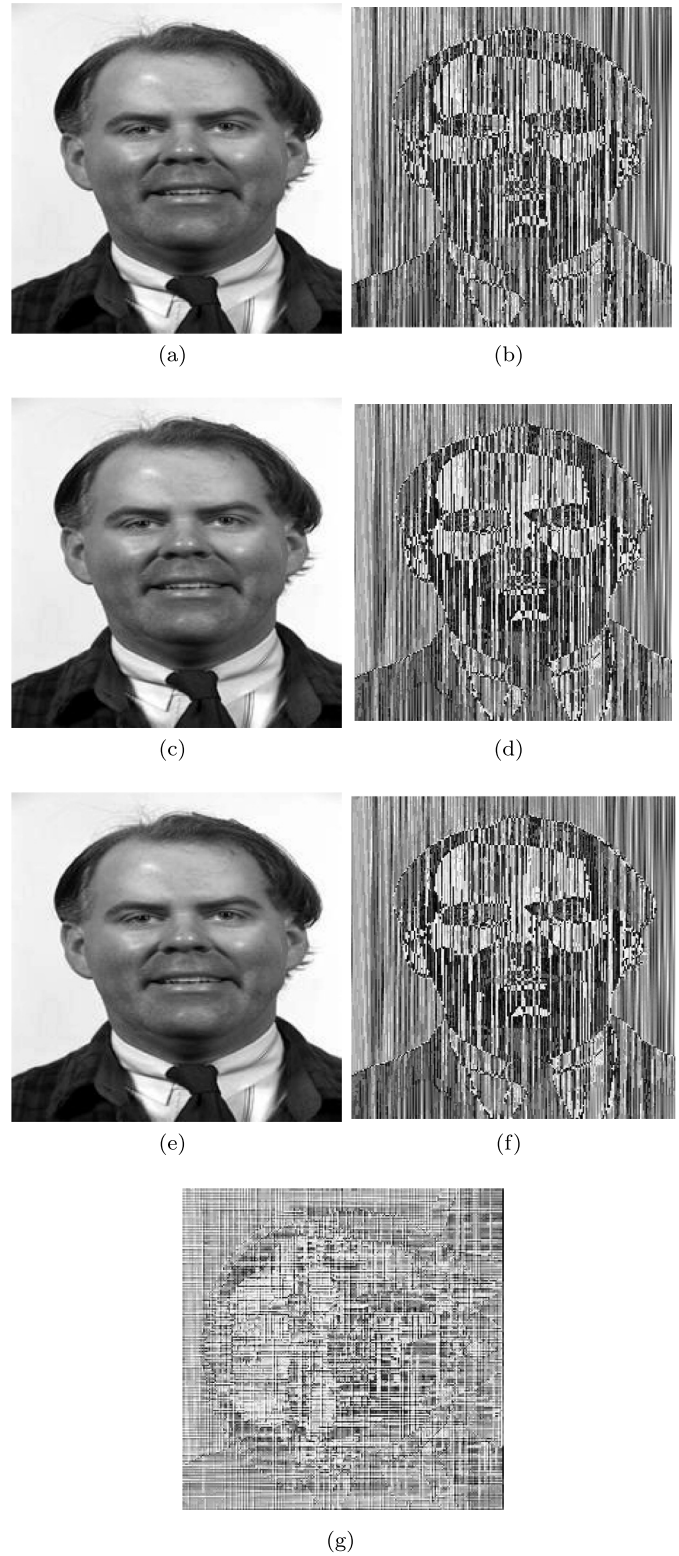
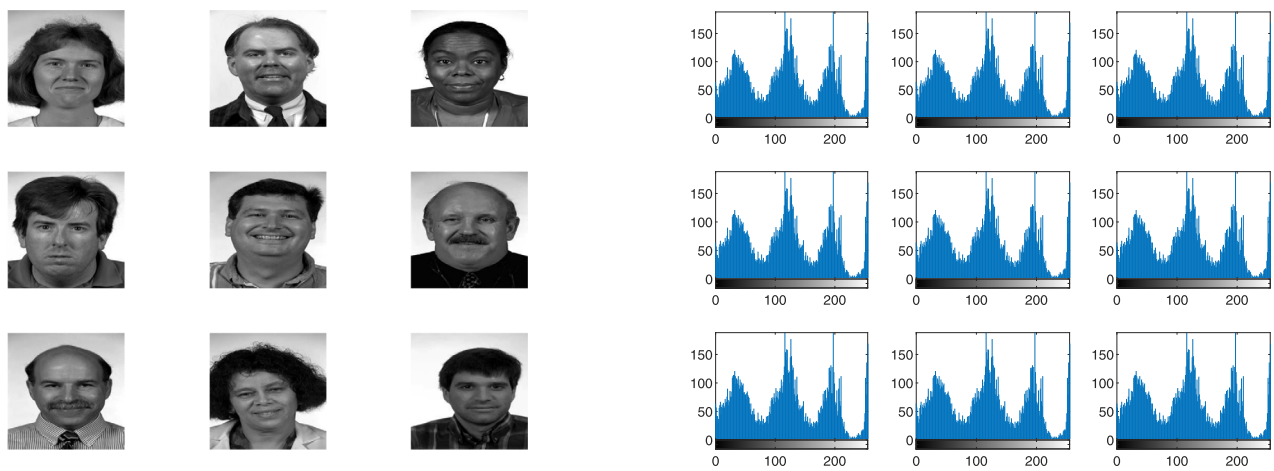



**Fig. 12.** Encryption stages of a color face with the FO Lorenz chaotic system (a) R component, (b) encrypted R component, (c) G component, (d) encrypted G component, (e) B component, (f) encrypted B component, (g) generated cancellable template.



(a) (b)

**Fig. 13.** Samples of FERET dataset (a) original face images, (b) histograms of original faces.

The structure of the DWT is illustrated in Fig. 9. The set of parallel filters constitutes a filter bank. By decimation of the outputs of $H_0$ and $G_0$, we set all odd samples to zero. This process is equivalent to multiplying by $\frac{1}{2}[1+(-1)^n]$. To allow perfect construction PR, $X(z)$ must be equal to $Y(z)$. Hence, $Y(z)$ is evaluated with the following expression:

$$\begin{aligned} Y(z) &= \frac{1}{2}\{X_0(z)+X_0(-z)\}G_0(z)+\frac{1}{2}\{X_1(z)+X_1(-z)\}G_1(z) \\ &= \frac{1}{2}X(z)\{H_0(z)G_0(z)+H_1(z)G_1(z)\} \\ &\quad +\frac{1}{2}X(-z)\{H_0(-z)G_0(z)+H_1(-z)G_1(z)\} \end{aligned} \tag{16}$$

To achieve the first PR condition, the term multiplied by $X_0(z)$ is forced to zero. In other words, $H_0(-z)G_0(-z)+H_1(-z)G_1(-z)=0$. This can be achieved by using $H_1(z)=z^{-p}G_0(-z)$ and $G_1(z)=z^pH_0(-z)$, where $p$ is odd and given by $p=\pm 1$. The second PR condition is $H_0(z)G_0(z)+H_1(z)G_1(z)=2$. We can set $H_0(z)G_0(z)=P(z)$. By substituting for $H_1(z)=z^{-p}G_0(-z)$ into $H_0(-z)G_0(-z)+H_1(-z)G_1(-z)=0$, we get the following equation:

$$P(z)+P(-z)=2 \tag{17}$$

The above equation is satisfied if and only if the polynomial $P(z)$ has $p_0=1$ and $p_n=0$ for all even. Hence, $P(z)$ has the following expression:

$$P(z)=\cdots+p_5z^5+p_3z^3+p_1z+1+p_1z^{-1}+p_3z^{-3}+p_5z^{-5}+\cdots \tag{18}$$

Maximum fusion rule is applied to obtain the cancellable templates as illustrated in Fig. 10.

### 4.3. Circuit realization of the FO Lorenz chaotic system

Circuit realization of the FO Lorenz chaotic system is essential for testing the dynamic behavior of the proposed cancellable face recognition scheme of Eqn. (12). Fig. 11 shows the implementation of the FO Lorenz chaotic system. The circuit in Fig. 11 is built using common electronic components such as the TL082 operational amplifier with a voltage supply $\pm 15V$ to perform several functions at the same time such as integration, differentiation, subtraction, and addition. To realize the nonlinear functions $x.z$ and $x.y$, we have to use the AD633 multiplier, and RC elements [1]. The authors of [1] selected $R_4=R_{10}=R_{15}=R_{18}=R_{23}=1k\Omega$, $R_5=R_8=R_9=R_{16}=R_{24}=R_{25}=R_{26}=10k\Omega$, $R_6=R_7=2k\Omega$, $R_{14}=20k\Omega$, $R_{17}=715\Omega$ and $R_{22}=7.5k\Omega$ as shown in [53]. The transfer function of RC elements which represent the approximation of the FO capacitor of order 0.995 is given in Eqn. (19), according to Oustaloup approximation method [54], The authors of [1] selected the values of RC elements $R_1=R_{11}=R_{19}=62.84M\Omega$, $R_2=R_{12}=R_{20}=250k\Omega$, $R_3=R_{13}=R_{21}=2.5k\Omega$, $C_1=C_4=C_7=1.23\mu F$, $C_2=C_5=C_8=1.84\mu F$ and $C_3=C_6=C_9=1.1\mu F$.

$$\begin{aligned} H(s) &= \frac{\frac{C_0}{C_1}}{s+\frac{1}{R_1C_1}}+\frac{\frac{C_0}{C_1}}{s+\frac{1}{R_2C_2}}+\frac{\frac{C_0}{C_1}}{s+\frac{1}{R_3C_3}} \\ &= \frac{1}{s^{0.9}}=\frac{2.2675(s+1.292)(s+215.4)}{(s+0.01292)(s+2.154)(s+359.4)} \end{aligned} \tag{19}$$

## 5. Evaluation metrics and simulation results based on the three datasets

In this paper, we used samples of FERET [55], LFW [56], and ORL datasets [57] as shown in Figs. 13a, 15a, and 17a, respectively. The reason for using these three datasets is that they have different facial expressions, orientations and illumination conditions. The resolutions of all color face images in FERET and LFW datasets are $227\times 227$, but the resolution of ORL gray-scale images is $128\times 128$.

Generally, we can use different metrics in order to evaluate the power of the proposed cancellable face recognition scheme. Average correlation between new and stored cancellable biometric templates is one of the metrics that are widely employed to evaluate the efficiency of the cancellable biometric scheme. The correlation between two biometric templates is given by:

$$R_{xy}=\frac{\frac{1}{M}\sum_{i=1}^{M}(x_i-\bar{x})(y_i-\bar{y})}{\sigma_x\sigma_y} \tag{20}$$

where $M$ is equal to the total number of pixels in each template, $x$ and $y$ are the encrypted biometric templates. We estimate two probability distributions for correlation scores of genuine and impostor users. The intersection point between these distributions determines the EER [58] [59]. Moreover, the ROC curve is one of

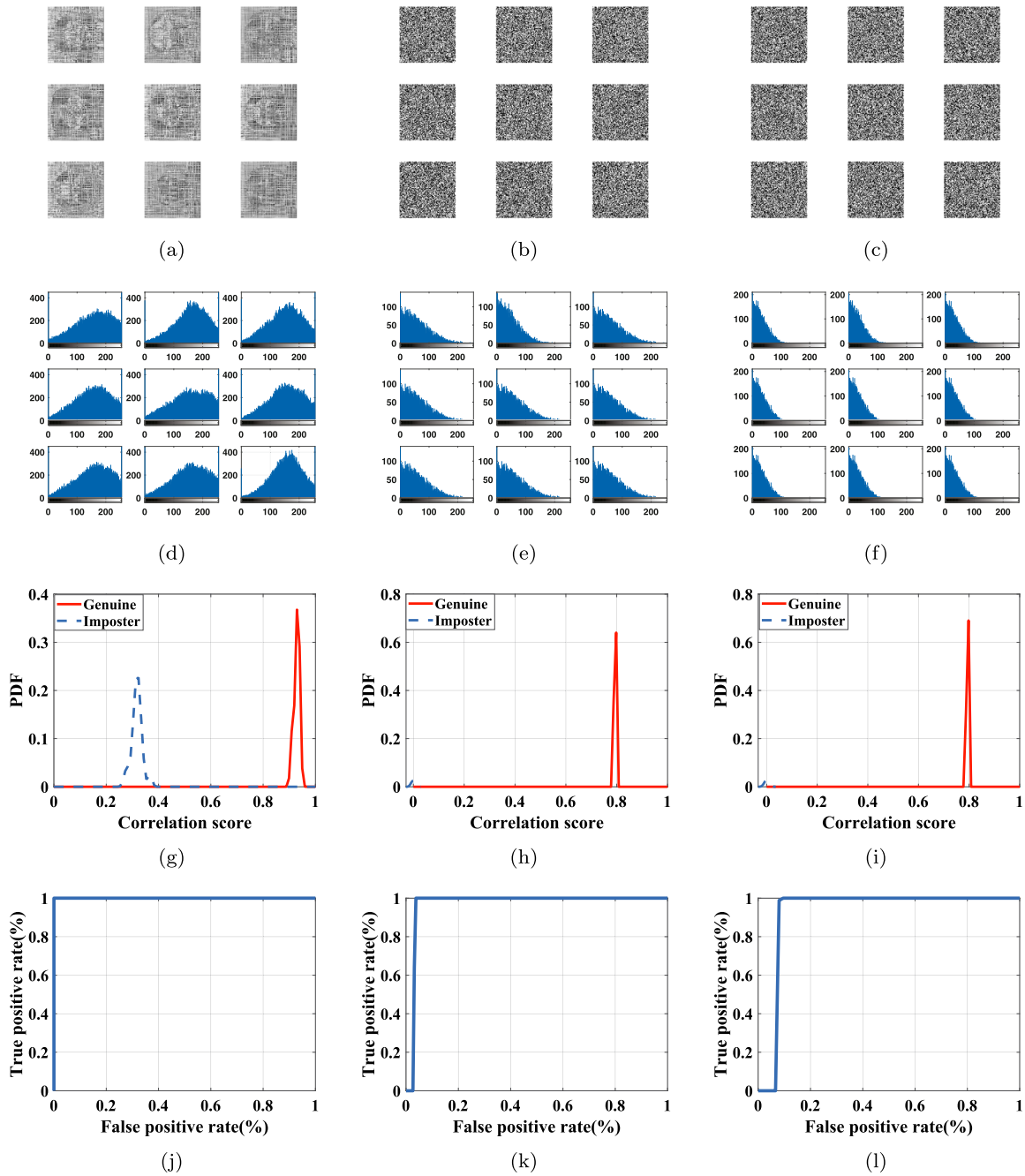



**Fig. 14.** Results on FERET dataset (a) encrypted faces with the proposed FO Lorenz chaotic system, (b) encrypted faces with RP after homomorphic transform scheme [31], (c) encrypted faces with Gaussian RP after IFL scheme [31], (d) histograms of images in (a), (e) histograms of images in (b), (f) histograms of images in (c), (g) Probability Density Functions (PDFs) for the proposed scheme, (h) PDFs for cancellable face recognition based on RP after homomorphic transform scheme [31], (i) PDFs for cancellable face recognition based on Gaussian RP after IFL scheme [31], (j) ROC curve for the proposed scheme, (k) ROC curve for cancellable face recognition based on RP after homomorphic transform scheme [31], (l) ROC curve for cancellable face recognition based on Gaussian RP after IFL scheme [31].

the most popular metrics that can be used for biometric system evaluation. The ROC curve is generated by plotting the False Positive Rate (FPR) on the $x$ axis and True Positive Rate (TPR) on the $y$ axis [60]. Both TPR and FPR are given in Eq. (21) and (22), respectively.

$$FPR = \frac{F_P}{F_P + T_N} \tag{21}$$

$$TPR = \frac{T_P}{T_P + F_N} \tag{22}$$

where $T_P$ represents the true positive value, $F_P$ denotes false the positive value, $T_N$ is the true negative value and $F_N$ represents the false negative value. The False Reject Rate (FRR) means the misclassified genuine record treated as impostor.

In this part, we evaluate the performance of the proposed scheme, which has been described above. Furthermore, we compare it with other different cancellable biometric recognition schemes from several perspectives such as effectiveness of encryption of face images, histograms of face images, AROC, correlation scores, to appraise the performance of the recommended scheme based on the FERET, LFW, and ORL datasets.

We verify the efficacy of the proposed scheme by comparison with the Gaussion RP after IFL and Gaussion RP after homomorphic transform. Some facial images are shown in Fig. 13a. They are

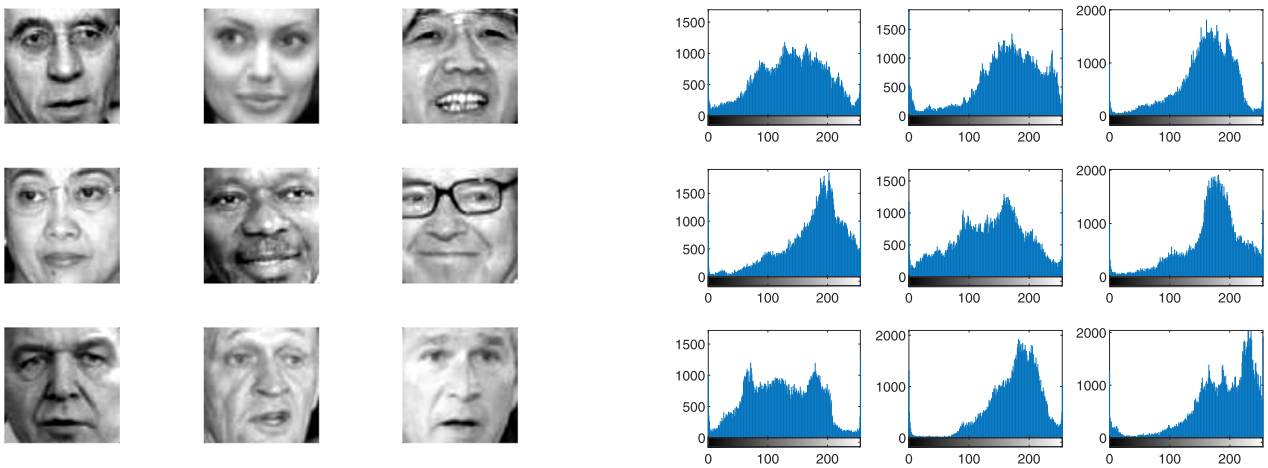



**Fig. 15.** Samples of LFW dataset (a) original face images, (b) histograms of original faces.

**Table 2**
Results on LFW dataset.

| | Proposed Scheme | Gaussian RP after IFL scheme [31] | RP after homomorphic transform scheme [31] |
|---|---|---|---|
| Average correlation of licensed users | 0.9334 | 0.7925 | 0.7938 |
| Average correlation of unlicensed users | 0.3626 | -2.4666e-04 | -0.0014 |
| EER | 0 | 0.4723 | 0.0053 |
| FAR | 0 | 0.0350 | 0.0262 |
| FRR | 0 | 0.9393 | 0.0070 |
| AROC | 1 | 0.9680 | 0.9791 |
| Variance of licensed users | 2.9439e-05 | 3.7476e-06 | 4.1428e-06 |
| Variance of unlicensed users | 7.3485e-04 | 3.8352e-05 | 3.0621e-05 |

**Table 3**
Results on FERET dataset.

| | Proposed Scheme | Gaussian RP after IFL scheme [31] | RP after homomorphic transform scheme [31] |
|---|---|---|---|
| Average correlation of licensed users | 0.9283 | 0.7930 | 0.7939 |
| Average correlation of unlicensed users | 0.3173 | 5.9159e-04 | -0.0016 |
| EER | 0 | 0.4016 | 0.0191 |
| FAR | 0 | 0.0335 | 0.0469 |
| FRR | 0 | 0.7989 | 0.0312 |
| AROC | 1 | 0.9695 | 0.9629 |
| Variance of licensed users | 1.0524e-04 | 4.7433e-06 | 3.2173e-06 |
| Variance of unlicensed users | 4.0476e-04 | 6.2590e-05 | 6.5960e-05 |

encrypted in Figs. 14 (a)-(c). Fig. 13b displays the histogram distributions for the original biometric samples obtained from FERET dataset. In addition, the histogram distributions of encrypted test sample images are presented in Figs. 14 (d)-(f) for the proposed scheme and the related schemes (RP after Homomorphic transform and RP after IFL). The obtained histogram distributions of these encrypted samples are obviously very different from those of the original ones.

The probability distributions of the correlation coefficient values of licensed and unlicensed users are shown in Figs. 14 (g)-(i). The ROC curves are shown in Figs. 14 (j)-(l). These figures for the proposed and related cancellable face recognition schemes indicate that the AROC value reaches 100% for the proposed cancellable face recognition, which ensures the robustness of this scheme.

All metric values are summarized in Table 3 to evaluate the strength of all cancellable face recognition schemes. From this table, we ensure that the proposed cancellable biometric recognition scheme has the highest AROC values that are close to 1, and the lowest EER values. The average correlation values of licensed users is higher than the counterparts of related schemes.

Figs. 15, and 16 present the simulation results on the LFW dataset. Furthermore, Table 2 includes all evaluation metrics of the proposed and related cancellable face recognition schemes on the LFW dataset. The same tests are also applied on the ORL dataset.

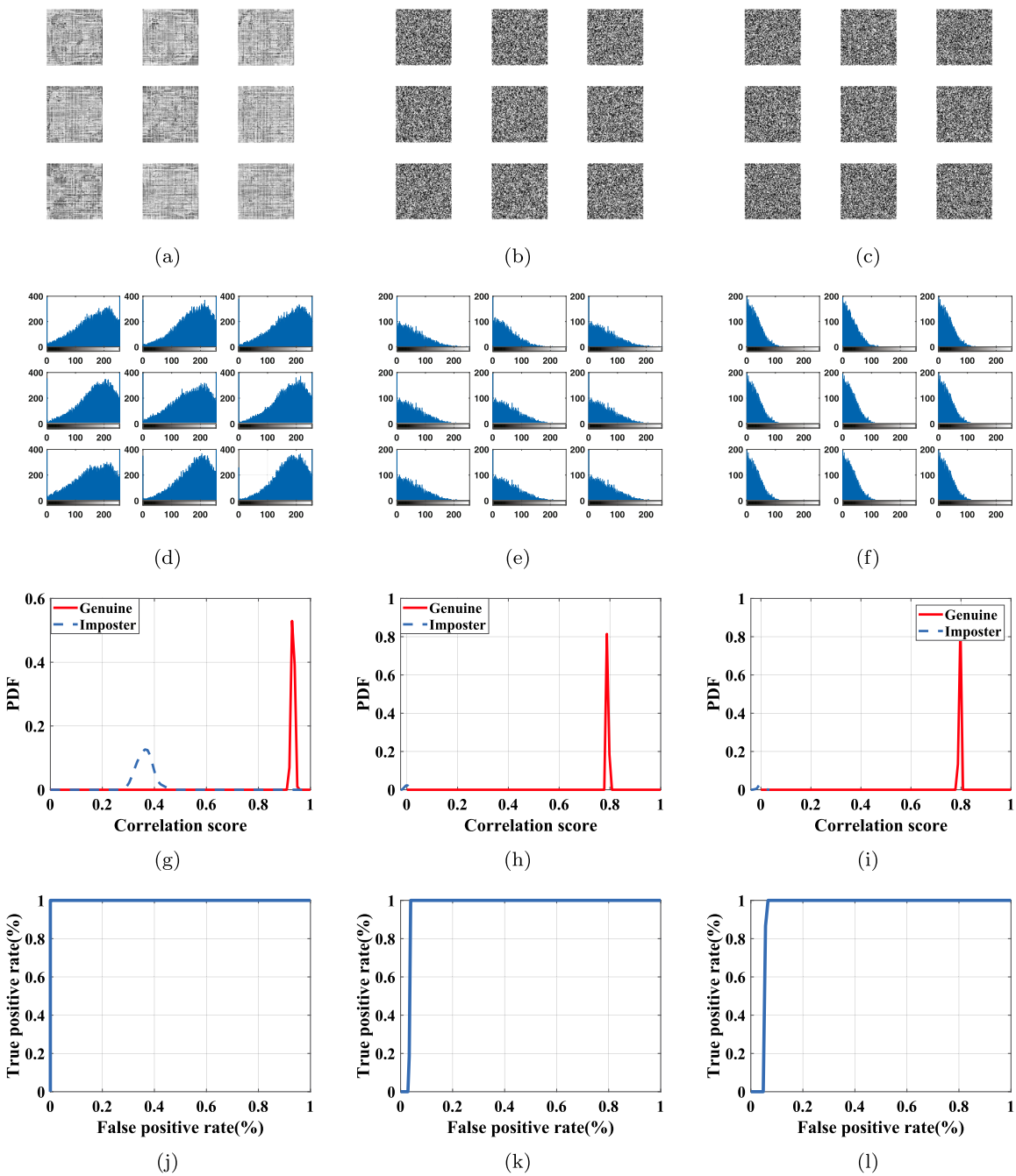



**Fig. 16.** Results on LFW dataset (a) encrypted faces with the proposed FO Lorenz chaotic system, (b) encrypted faces with RP after homomorphic transform scheme [31], (c) encrypted faces with Gaussian RP after IFL scheme [31], (d) histograms of images in (a), (e) histograms of images in (b), (f) histograms of images in (c), (g) Probability Density Functions (PDFs) for the proposed scheme, (h) PDFs for cancellable face recognition based on RP after homomorphic transform scheme [31], (i) PDFs for cancellable face recognition based on Gaussian RP after IFL scheme [31], (j) ROC curve for the proposed scheme, (k) ROC curve for cancellable face recognition based on RP after homomorphic transform scheme [31], (l) ROC curve for cancellable face recognition based on Gaussian RP after IFL scheme [31].

The main difference between the ORL dataset and the FERET and LFW datasets is that the ORL dataset contains gray-scale images. Hence, we perform XOR on a single component. Simulation results on the ORL dataset are shown in Fig. 18. Moreover, the obtained results on the ORL dataset are summarized in Table 4. Table 5 shows the computational cost of the proposed scheme compared with two other counterparts [31] on MATLAB Intel(R) Core(TM) $i$7-4800MQ on a CPU with a 2.70$GHz$ processor. A comparison study with two published cancellable face recognition schemes reveals the superiority of the proposed scheme with lower EER, higher AROC and lower computational cost as presented in Table 5 (see also Table 6).

## 6. Conclusion and future work

This paper presented a cancellable face recognition scheme that depends on FO Lorenz chaotic system. The proposed scheme introduces some sort of partial encryption of color or gray-scale face images through XORing of image components with a time series created from the FO Lorenz chaotic system. Some post-processing is implemented on the color components of color images, and

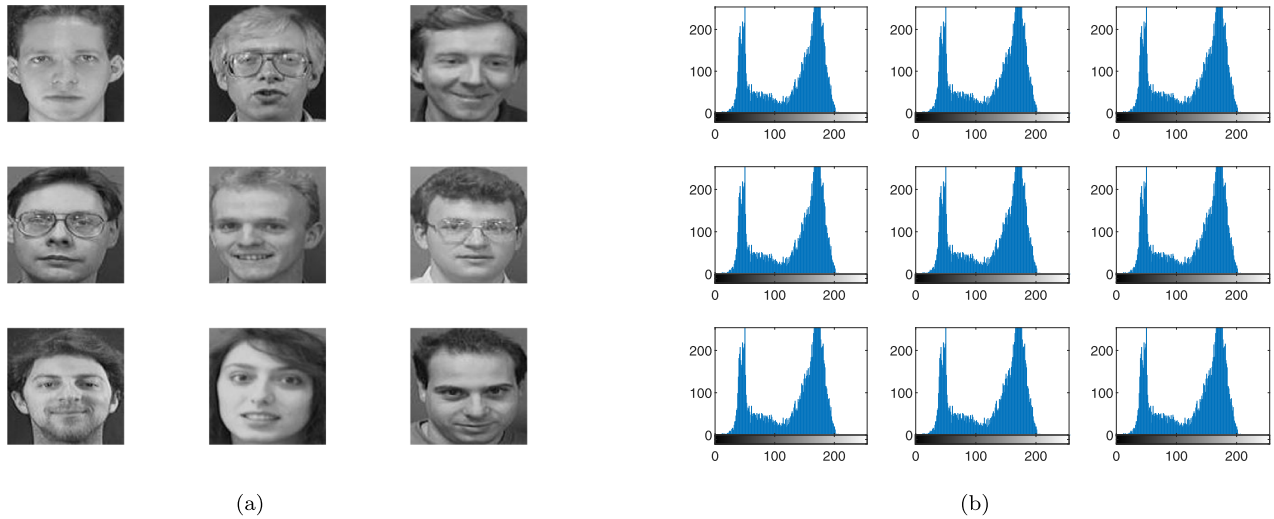



**Fig. 17.** Samples of ORL dataset (a) original face images, (b) histograms of original faces.

**Table 4**
Results on ORL dataset.

| | Proposed Scheme | Gaussian RP after IFL scheme [31] | RP after homomorphic transform scheme [31] |
|---|---|---|---|
| Average correlation of licensed users | 0.9429 | 0.7977 | 0.7939 |
| Average correlation of unlicensed users | 0.2479 | 2.1823e-04 | -6.1422e-04 |
| EER | 0 | 0.0112 | 0.0230 |
| FAR | 0 | 0.0243 | 0.0420 |
| FRR | 1 | 0.0196 | 0.0397 |
| AROC | 1 | 0.9799 | 0.9669 |
| Variance of licensed users | 1.8815e-05 | 9.4331e-06 | 3.2524e-06 |
| Variance of unlicensed users | 5.2167e-04 | 4.5505e-05 | 7.1261e-05 |

**Table 5**
Computational cost in second for the proposed scheme and two related schemes.

| Framework | time(s) |
|---|---|
| RP after homomorphic transform scheme [31] | 12.188 |
| Gaussian RP after IFL scheme [31] | 13.14 |
| Proposed scheme | 1.32244 |

**Table 6**
Comparison between different cancellable biometric schemes based on AROC.

| Method | AROC |
|---|---|
| Proposed scheme on ORL dataset | 1 |
| Proposed scheme on FERET dataset | 1 |
| Proposed scheme on LFWT dataset | 1 |
| Gaussian RP after IFL scheme (ORL) [31] | 0.9720 |
| RP after homomorphic transform scheme (ORL) [31] | 0.9774 |
| Gaussian RP after IFL scheme (FERET) [31] | 0.9744 |
| RP after homomorphic transform scheme (FERET) [31] | 0.9294 |
| Gaussian RP after IFL scheme (LFW) [31] | 0.9668 |
| RP after homomorphic transform scheme (LFW) [31] | 0.9694 |
| Scheme in [28] | 0.998 |
| Scheme in [29] | 0.9997 |
| Scheme in [30] | 0.9984 |

finally wavelet fusion is performed as a non-invertible process for merging color components into a single cancellable template for each face image. Simulation results on different datasets revealed the success of the proposed cancellable face recognition scheme in hiding of facial features, while keeping high AROC values and low EER values. A comparison study with two published cancellable face recognition schemes revealed superiority of the proposed scheme. This is attributed to the good selection of the FO Lorenz chaotic system parameters to yield random variables with as uniform distributions as possible. In addition, the proposed scheme can be realized using the Orcad PSPICE software. Moreover, the computational cost of the proposed scheme is less than those of the other schemes included in the comparison. Hence, the proposed scheme can be used in security and verification applications. The drawback of the proposed scheme is that the obtained encrypted faces are partially encrypted only. There is more space for research towards full encryption of faces with FO Lorenz chaotic system. In addition, there is a need to introduce other FO chaotic systems and compare them with the Lorenz system. The non-linearity of the system needs to be enhanced to achieve more robustness.

## CRediT authorship contribution statement

**Iman S. Badr:** Conceptualization, Data curation, Software, Visualization, Writing – original draft. **Ahmed G. Radwan:** Resources, Software, Supervision, Validation, Writing – review & editing. **El-Sayed M. EL-Rabaie:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Lobna A. Said:** Data curation, Resources, Software, Validation, Writing – review & editing. **Ghada M. El Banby:** Conceptualization, Formal analysis, Investiga-

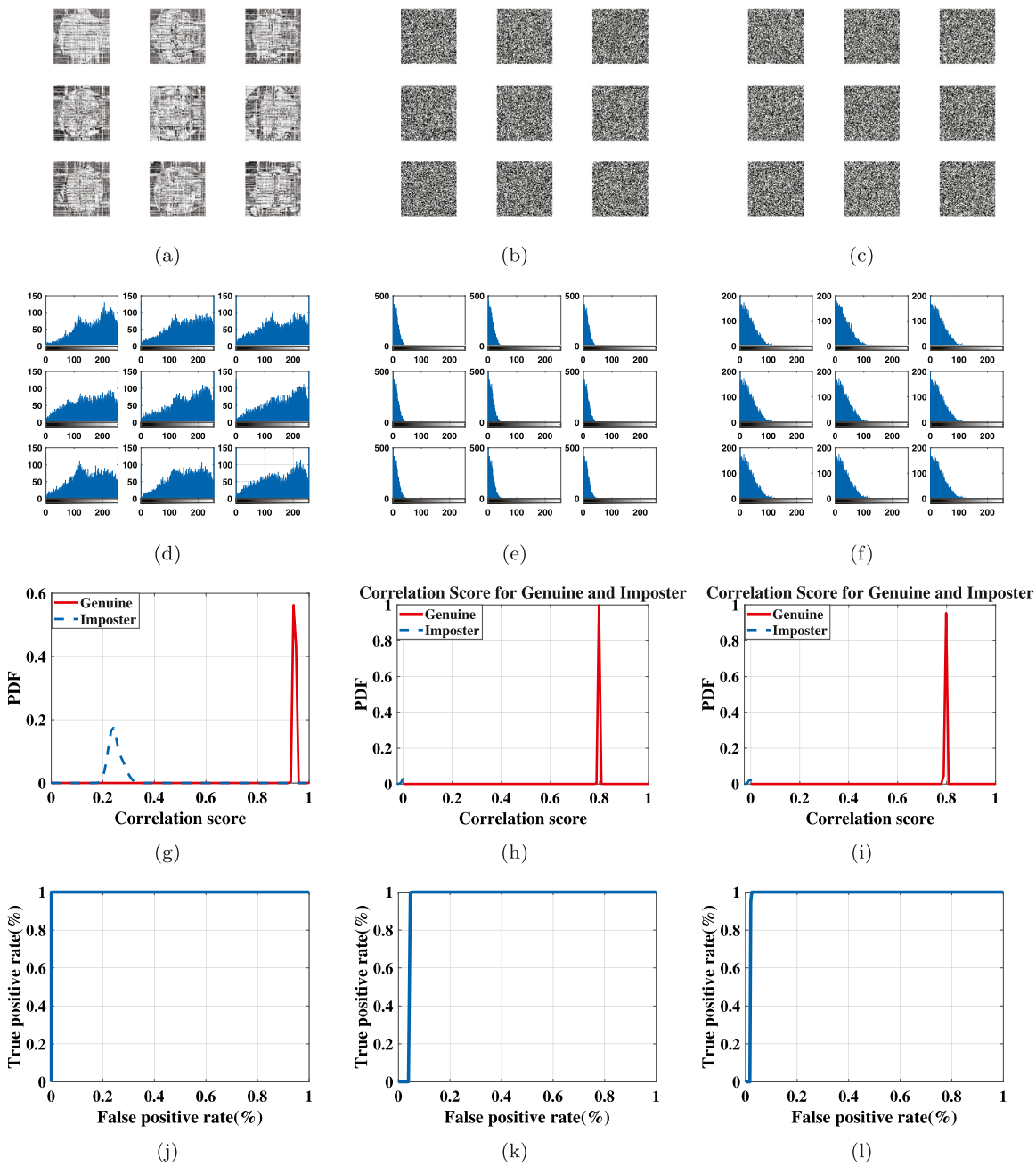



**Fig. 18.** Results on ORL dataset (a) encrypted faces with the proposed FO Lorenz chaotic system, (b) encrypted faces with RP after homomorphic transform scheme [31], (c) encrypted faces with Gaussian RP after IFL scheme [31], (d) histograms of images in (a), (e) histograms of images in (b), (f) histograms of images in (c), (g) Probability Density Functions (PDFs) for the proposed scheme, (h) PDFs for cancellable face recognition based on RP after homomorphic transform scheme [31], (i) PDFs for cancellable face recognition based on Gaussian RP after IFL scheme [31], (j) ROC curve for the proposed scheme, (k) ROC curve for cancellable face recognition based on RP after homomorphic transform scheme [31], (l) ROC curve for cancellable face recognition based on Gaussian RP after IFL scheme [31].

tion, Methodology, Software, Validation, Visualization. **Walid El-Shafai:** Conceptualization, Formal analysis, Methodology, Software, Validation, Writing – review & editing. **Fathi E. Abd El-Samie:** Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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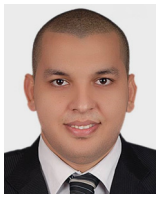

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