Dual Optical Encryption for Binary Data and Secret Key Using Phase-shifting Digital Holography

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In this paper, we propose a new dual optical encryption method for binary data and secret key based on 2-step phase-shifting digital holography for a cryptographic system. Schematically, the proposed optical setup contains two Mach-Zehnder type interferometers. The inner interferometer is used for encrypting the secret key with the common key, while the outer interferometer is used for encrypting the binary data with the same secret key. 2-step phase-shifting digital holograms, which result in the encrypted data, are acquired by moving the PZT mirror with phase step of 0 or $\pi/2$ in the reference beam path of the Mach-Zehnder type interferometer. The digital hologram with the encrypted information is a Fourier transform hologram and is recorded on CCD with 256 gray level quantized intensities. Computer experiments show the results to be encryption and decryption carried out with the proposed method. The decryption of binary secret key image and data image is performed successfully.

Keywords : Optical encryption, Digital holography, Phase-shifting interferometry, Cryptosystem

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I. INTRODUCTION

Nowadays, as the communication network such as the internet and mobile net develops, multimedia contents are expanding. Despite widespread use of digital multimedia data, there have been threats and attacks to information in communication systems. For this reason, information security becomes very important and necessary. In order to protect original information such as multimedia data, a number of electronic or optical cryptosystems have been proposed. One of the simple methods to ensure security is considering all data as binary strings and encrypting them using encryption algorithms such as DES(Data Encryption Standard) or AES (Advanced Encryption Standard). [1] Encryption is the process of transforming the plain data to the cipher data by a security key (such as a common key or a secret key) to ensure its security. In order for an authorized user to decrypt the cipher, the same correct security key has to be known to the authorized user. In conventional symmetric

key cryptography, the security key is opened by all the users as a common key which is not transmitted to users. Therefore, this type of algorithm has a weak point against data interception by an unauthorized user. Since a security key is the core of most data cryptosystems, the protection of the security key is also very important. In general, when the multimedia data is static, it can be treated as binary data and the conventional electronic encryption methods can be used. However, these methods involve amounts of computations and are not fast enough for high-volume multimedia data. [2] Recently, various kinds of optical encryption techniques have been proposed for security systems because optical systems have merits of parallel processing and fast operation. [3-11] Among them the optical information is composed of complex function which is in phase and amplitude forms, and in order to get the complex encrypted data, a holographic recording technique may be required. This requirement makes it difficult to store and transmit the encrypted information over a digital network. However, optical encryption

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$$C(\alpha, \beta) = |C(\alpha, \beta)|e^{j\phi_c(\alpha, \beta)}. \quad (4)$$

Then, the digital holographic intensity pattern recorded by the CCD1 at the spatial frequency plane is given by

$$\begin{aligned} I(\alpha, \beta) &= |S(\alpha, \beta) + C(\alpha, \beta)|^2 \\ &= |S(\alpha, \beta)|^2 + |C(\alpha, \beta)|^2 + 2|S(\alpha, \beta)||C(\alpha, \beta)|\cos \Delta\phi_{sc}. \end{aligned} \quad (5)$$

with the object beam and the reference beam given by Eqs. (2) and (4), where $\Delta\phi_{sc} = \phi_s - \phi_c$ is the phase difference between the object and the reference beams. The phase-shifting interferometry method gives the exact reconstruction of the phase difference between the object and the reference beams and amplitude of these two beams. Two intensity patterns in the form of digital holograms are achieved by 2-step phase-shifting digital holography with the reference beam phase shifted by 0 or $\pi/2$. The PZT mirror can allow phase shift with phase steps of $\pi/2$ by moving the mirror properly. This 2-step phase-shifting digital holography has a merit of the reduced number of holograms compared to multi-step phase-shifting holography. By rewriting Eq. (5), 2-step phase-shifting digital holograms are represented as

$$\begin{aligned} I_1(\alpha, \beta) &= |S(\alpha, \beta)|^2 + |C(\alpha, \beta)|^2 + 2|S(\alpha, \beta)||C(\alpha, \beta)|\cos \Delta\phi_{sc} \\ I_2(\alpha, \beta) &= |S(\alpha, \beta)|^2 + |C(\alpha, \beta)|^2 + 2|S(\alpha, \beta)||C(\alpha, \beta)|\cos(\Delta\phi_{sc} - \pi/2). \end{aligned} \quad (6)$$

These two digital holograms are encrypted data, which are stored in a computer and transmitted through the digital communication network.

After DC-term removal technique is applied to Eq. (6), the phase difference of object beam and reference beam and the magnitude are calculated as follows. [22]

$$\Delta\phi_{sc} = \Delta\phi_s - \Delta\phi_c = \tan^{-1}\left(\frac{I_1'}{I_2'}\right). \quad (7)$$

$$|S(\alpha, \beta)||C(\alpha, \beta)| = \frac{1}{2}\sqrt{(I_1')^2 + (I_2')^2}. \quad (8)$$

where I_1' and I_2' are modified holographic intensities after DC-term removal.

From Eqs. (7) and (8), the complex hologram1 with secret key encryption information is expressed as

$$H_1(\alpha, \beta) = |S(\alpha, \beta)||C(\alpha, \beta)|e^{j(\phi_s - \phi_c)}. \quad (9)$$

Similarly, we can encrypt binary data or image with the secret key. Let $b(x, y)$ be binary data or image to be encrypted and $\exp[j\theta_b(x, y)]$ be a random phase pattern. The multiplication of the two is represented as

$$b(x, y) = |b(x, y)|e^{j\theta_b(x, y)}. \quad (10)$$

The Fourier transform of $b(x, y)$ is expressed as

$$B(\alpha, \beta) = |B(\alpha, \beta)|e^{j\phi_b(\alpha, \beta)}. \quad (11)$$

Then, the digital holographic intensity pattern recorded by the CCD2 at the spatial frequency plane is given by

$$\begin{aligned} I(\alpha, \beta) &= |B(\alpha, \beta) + S(\alpha, \beta)|^2 \\ &= |B(\alpha, \beta)|^2 + |S(\alpha, \beta)|^2 + 2|B(\alpha, \beta)||S(\alpha, \beta)|\cos \Delta\phi_{bs}, \end{aligned} \quad (12)$$

with the object beam and the reference beam given by Eqs. (11) and (2), where $\Delta\phi_{bs} = \phi_b - \phi_s$ is the phase difference between the object and the reference beams.

After carrying out the 2-step phase-shifting digital holographic method, the phase difference of object beam and reference beam and the magnitude are acquired as follows.

$$\Delta\phi_{bs} = \Delta\phi_b - \Delta\phi_s = \tan^{-1}\left(\frac{I_3'}{I_4'}\right). \quad (13)$$

$$|B(\alpha, \beta)||S(\alpha, \beta)| = \frac{1}{2}\sqrt{(I_3')^2 + (I_4')^2}. \quad (14)$$

where I_3' and I_4' are modified holographic intensities after DC-term removal.

From Eqs. (13) and (14), the complex hologram2 with data encryption information is expressed as

$$H_2(\alpha, \beta) = |B(\alpha, \beta)||S(\alpha, \beta)|e^{j(\phi_b - \phi_s)}. \quad (15)$$

In order to get the complex distribution $B(\alpha, \beta)$ and decrypt the original binary data or image, we need the complex distribution $S(\alpha, \beta)$ of the secret key. Note that it is possible to get $S(\alpha, \beta)$ by Eq. (9) with knowledge of the complex hologram1 because the Fourier transform pattern of the secret key, Eq. (4), is acquired by the opened and known binary common key code of $c(x, y)$. We need the intensity distribution $|C(\alpha, \beta)|^2$ of the common key in order to reconstruct $S(\alpha, \beta)$. This intensity $|C(\alpha, \beta)|^2$ is acquired when we get the DC-term information on the CCD1 by removing the object beam in the optical setup shown in fig. 1, which is done by closing the shutter S1, S3 and opening the shutter S2 only. And we also need the intensity distribution $|S(\alpha, \beta)|^2$ of the secret key in order to reconstruct $B(\alpha, \beta)$. Similarly, the only object beam intensity recorded on the CCD2 gives $|S(\alpha, \beta)|^2$ by closing the shutter S1, S2 and opening the shutter S3 in the optical setup shown in fig. 1. Using the complex hologram1, hologram2 and the common key, the reconstructed complex

FIG. 2. Block diagram of the dual encryption/decryption procedure.

FIG. 3. A binary pattern for computer simulations (256×256 pixels): (a) a binary bit code (a random generated code) as a common key, (b) a binary image (Girl1) as a secret key1 of user1, (c) a binary image (Girl2) as a secret key2 of user2, (d) a binary image (Monkey) to be encrypted and decrypted as information data.

distribution is obtained by

$$D_1(\alpha, \beta) = \frac{H_1(\alpha, \beta)C(\alpha, \beta)}{|C(\alpha, \beta)|^2} = \frac{|S(\alpha, \beta)|C(\alpha, \beta)e^{j(\phi_0 - \phi_c)}|C(\alpha, \beta)|e^{j\phi_c}}{|C(\alpha, \beta)|^2} = |S(\alpha, \beta)|e^{j\phi_0(\alpha, \beta)} = S(\alpha, \beta). \quad (16)$$

$$D_2(\alpha, \beta) = \frac{H_2(\alpha, \beta)D_1(\alpha, \beta)}{|S(\alpha, \beta)|^2} = \frac{|B(\alpha, \beta)||S(\alpha, \beta)|e^{j(\phi_0 - \phi_s)}|S(\alpha, \beta)|e^{j\phi_s}}{|S(\alpha, \beta)|^2} = |B(\alpha, \beta)|e^{j\phi_0(\alpha, \beta)} = B(\alpha, \beta). \quad (17)$$

By using an inverse Fourier transformation, the original data information is reconstructed and the original binary data or image is decrypted after carrying out the proper threshold.

$$d(x, y) = F^{-1}[D_2(\alpha, \beta)] = F^{-1}[S(\alpha, \beta)] = s(x, y). \quad (18)$$

Figure 2 shows block diagram of dual encryption and decryption procedure.

III. COMPUTER EXPERIMENTS

We show the performance of the proposed dual optical

encryption method by computer simulations. The binary bit code of size 256×256 pixels shown in Fig. 3(a) is used as the common key which is random generated for convenience, and the binary images (Girl1 and Girl2) of size 256×256 pixels shown in Fig. 3(b) and (c) are used as the user's secret keys to be encrypted, respectively. These secret keys can be interpreted as the user's own watermark images for authentication cryptography. The binary image data of size 256×256 pixels shown in Fig. 3(d) is used as input data to be encrypted by the user's secret key.

Figure 4 shows an example of the encrypted digital holograms which are recorded on CCDs. Each hologram is quantized with 256 gray levels. The histogram of the encrypted secret key1 shown in Fig. 4(a), which has a uniform and random gray-level distribution, is the one of the acquired 256 gray level histogram patterns using 2-step phase-shifting digital holography. Similarly, Fig. 4(b) shows the one of the acquired 256 gray level histogram patterns of the encrypted binary image using 2-step phase-shifting digital holography.

From the complex holograms calculated by the retrieved phase and amplitude from the encrypted data, reconstruction and decryption of the encrypted secret key and the encrypted image are carried out successfully. For example, Fig. 5(a) shows the reconstructed secret key1 image pattern when the correct common key is used for the secret key decryption. Fig. 5(b) is the decrypted binary image (Girl1) after binarization with the proper threshold. The decrypted binary image is the exact same original secret key1 image and

FIG. 4. Example of the encrypted digital holograms (256×256 pixels) with 256 gray levels obtained by using 2-step phase-shifting digital holography: (a) the histogram of the encrypted secret key1 (Girl1), (b) the histogram of the encrypted binary image (Monkey).

FIG. 5. Result of decryption for the secret key1 shown in FIG. 3 (b) when the same common key is used: (a) a reconstructed image pattern by decryption process, (b) a decrypted binary image (Girl1) after binarization with the proper threshold value, (c) a phase map representation of the Fourier transform of the reconstructed the secret key1 by the reconstructed complex hologram1 and the common key.

FIG. 6. Result of decryption for the binary image shown in FIG. 3(d) when the secret key1 of user1 is used: (a) a reconstructed image pattern by decryption process, (b) a graph showing the signal bits of the 100th row of the reconstructed image in FIG. 6(a), (c) a graph showing the noise bits of the 100th row of the reconstructed image in FIG. 6(a), (d) the correct decrypted binary image (Monkey) after binarization with the proper threshold value.

has no error when the same correct common key is used for decryption. This secret key can also be interpreted as watermark of the user1. Fig. 5(c) shows the phase map representation of the Fourier transform of the reconstructed secret key1 by the reconstructed complex hologram1 and the common key.

Figure 6(a) shows the reconstructed image pattern when the secret key1 of user1 is used for the encrypted hologram2

which is encrypted by the secret key1. We investigated the distribution of the pixel magnitude of the reconstructed image pattern and signal-to-noise ratio. One of the cross sections in the reconstructed image is shown in Fig. 6(b) and (c). The magnitude of the signal bits(one value in the original image) is about 1 in Fig. 6(b), but the magnitude of the noise bits(zero value in the original image) is below about 0.2 in Fig. 6(c). Since the magnitude of the signal

FIG. 7. Result of decryption for the binary image shown in FIG. 3 (d) when the secret key2 of user2 is used: (a) a reconstructed image pattern by decryption process, (b) a graph showing the signal bits of the 100th row of the reconstructed image in FIG. 7(a), (c) a graph showing the noise bits of the 100th row of the reconstructed image in FIG. 7(a), (d) the incorrect decrypted binary image after binarization with the same threshold value as in FIG. 6 (d).

bits is much greater than the magnitude of the noise bits, the reconstructed image can be decrypted into the original image when the proper threshold value is well defined. Fig. 6(d) is the decrypted binary image after binarization with the proper threshold value of 0.3. The decrypted binary image is the exact same original image data and has no error when the same correct secret key1 is used for decryption.

Figure 7(a) shows the reconstructed image pattern when the secret key2 of user2 is used for the encrypted hologram2 which is encrypted by the secret key1. This reconstructed pattern has a different intensity pattern (i.e. random pattern) compared to the one shown in Fig. 6(a). We also investigated the magnitude distribution of the cross section in the reconstructed image and signal-to-noise ratio. Fig. 7(b) and (c) show the results. Since the magnitude of the noise bits of some pixels are greater than the magnitude of signal bits, the proper threshold value cannot be defined. Therefore, the reconstructed image cannot be decrypted into the original image. Fig. 7(d) is the decrypted binary image after binarization with the same threshold value of 0.3.

IV. CONCLUSIONS

We propose a new dual optical encryption method for binary data and secret key based on 2-step phase-shifting digital holography for a cryptographic system. Dual optical encryption is implemented by constructing two Mach-Zehnder type interferometers simultaneously. The inner interferometer is used for encrypting the secret key with the common key, while the outer interferometer is used for encrypting the binary data with the same secret key. This proposed dual optical encryption method provides a more advanced cryptosystem to use double encryption in the binary data and has advantages of compactness and easy configuration of the optical system. For the case of applying the proposed method to encrypt a binary image data with a secret key image, a highly secure encryption is achieved. Computer experiments verified that the proposed method is perfect and suitable for cryptographic applications and secure communication systems.

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