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Modified computational integral imaging-based double image encryption using fractional Fourier transform

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ABSTRACT

In this paper, we propose an image encryption technique to simultaneously encrypt double or multiple images into one encrypted image using computational integral imaging (CII) and fractional Fourier transform (FrFT). In the encryption, each of the input plane images are located at different positions along a pickup plane, and simultaneously recorded in the form of an elemental image array (EIA) through a lenslet array. The recorded EIA to be encrypted is multiplied by FrFT with two different fractional orders. In order to mitigate the drawbacks of occlusion noise in computational integral imaging reconstruction (CIIR), the plane images can be reconstructed using a modified CIIR technique. To further improve the solution of the reconstructed plane images, a block matching algorithm is also introduced. Numerical simulation results verify the feasibility and effectiveness of the proposed method.

1. Introduction

Information security has been significant in the advancement of information techniques. Optical techniques have the distinct strength of processing complex two-dimensional (2D) or three-dimensional (3D) data in parallel and performing otherwise slow operations at great speeds. Many encryption algorithms have been reported based on different types of optical systems [1–5]. Among these, the most common are double random phase encoding in the Fourier domain, and more recently, in the fractional Fourier domain. An optical image encryption technique based on random phase encoding in the fractional Fourier transform (FrFT) domain was first presented by Unnikrishnan [6]. The remarkable advantage of optical encryption using FrFT is the fractional orders, which greatly enhance the key space and further increase the security of encryption systems. In some cases, two or multiple images with certain relationships, such as a series of plane images of objects or many different images, are encrypted into a single image to be stored or transmitted simultaneously. A number of encryption schemes for double or multiple images have been developed in recent years [7–11]. From the literature survey, it is clear that many researchers are studying the field of information security using their own methods, and most techniques have their own identity, advantages, and weaknesses.

Image processing techniques based on integral imaging are gaining increasing attention. The integral imaging technique was developed in 1908 by G. Lippmann [12] and was originally called integral photography. A general integral imaging system consists of two parts: pickup and reconstruction. In the pickup part, light rays emanating from input images passing through each lenslet are recorded using a 2D image sensor. The captured elemental images are considered as a set of demagnified 2D images because each set contains different perspective information about the input images. These demagnified 2D images are known as the elemental image array (EIA). For double image encryption, each of the double plane images is located at different positions along a pickup plane and simultaneously recorded in the form of a 2D EIA through a lenslet array. Reconstruction of the double images is a reverse pickup process performed by propagating the lights emanating from the elemental images through a similar lenslet array. Reconstruction can be achieved with two methods: optical integral imaging reconstruction (OIIR) [13,14] and computational integral imaging reconstruction (CIIR) [15–22]. To improve the OIIR problems of having certain limitations such as quality degradation of reconstructed images caused by light diffraction and limited optical devices, the CIIR techniques were developed to increase the resolution of the reconstructed images. CIIR can computationally reconstruct plane images by mapping elemental images using a virtual pinhole array based on ray optics.

In general, CIIR can clearly reconstruct plane images at the correct position from a virtual pinhole array. For double image reconstruction, the front plane image (near the pinhole array) can be clearly reconstructed on the correct place where the image was originally located at the pickup position, whereas another reconstructed image cannot be clearly reconstructed because the front image that is situated away from the output plane is unfocused

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and blocked as a result. In this paper, to overcome this problem, a binary mask based occlusion removal technique is introduced to remove the occlusion, and a block matching algorithm is utilized to restore the lost data in the occlusion removing process. To show the usefulness of the proposed method, we performed experiments and present the results in this paper.

2. Encryption and decryption

2.1. Double image pickup process

Double images can be picked up by a CII technique simultaneously. The light rays emanating from input plane images are captured by a lenslet array. The light rays passing through each lenslet are recorded using a 2D sensor. Fig. 1(a) describes the geometric principle of the double image pickup process used in the integral imaging system. Rays originating from the double images pass through the lenslet array and are captured as an EIA. The input image $I_0(y_0, z_0)$ is reproduced by the kth elemental lens and recorded at $y_{(c,k)}$ in the 2D image sensor. The pixel value $y_{(c,k)}$ of the kth elemental image of the image point $I_0(y_0, z_0)$ can be expressed as follows:

$$y_{(c,k)} = -\frac{f_0 f_c (k\phi - y_0)}{f_d (z_0 - f_0)} - \frac{f_c k\phi}{f_d} \quad (1)$$

where f_0 denotes the focal length of each elemental lens, f_d represents the distance between the focal plane of the lenslet array and the camera lens, f_c is the focal length of the charge-coupled device (CCD) camera lens, and ϕ is the size of each elemental lens. The disparity between the two adjacent elemental images is written as

$$\Delta y_{k_i k_{i+1}} = y_{(c,k_{i+1})} - y_{(c,k_i)} = \frac{f_0 f_c \phi (k_{i+1} - k_i)}{f_d (z_0 - f_0)} \quad (2)$$

2.2. Picked-up EIA encoded by FrFT

FrFT is an expanded version of the Fourier transform. We define the FrFT operation based on the fractional order α on the input image $f(x)$ as follows:

$$F^{\alpha}\{f(x)\}(\mu) = \int_{-\infty}^{+\infty} \kappa_{\alpha}(x,\mu) f(x) dx \quad (3)$$

For brevity, we describe only the one-dimensional (1D) case, where μ represents the αth fractional domain. The transform kernel $\kappa_{\alpha}(x,\mu)$ can be expressed as follows:

$$\kappa_{\alpha}(x,\mu) = \Re_{\theta} \exp\left[j\pi(x^2 \cot\theta - 2x\mu + \mu^2 \cot\theta)\right] \quad (4)$$

where $\theta = \alpha\pi/2$ and $\Re_{\theta}$ is a constant phase factor that is dependent on the fraction order α only. This definition is valid for values of $\alpha \neq 0$ or ± 2.

The encryption process-based FrFT is shown in Fig. 1(b), which can be described briefly as follows: the input EIA data $f(x)$ is multiplied by the first random phase mask (*RPM*) ($M1 = \exp[j2\pi n_1(x)]$); then, the FrFT operation applied by an order of α is given as

$$\psi(x) = F^{\alpha}\{f(x)\exp[j2\pi n_1(x)]\} \quad (5)$$

Now, the $\psi(x, y)$ is multiplied by the second RPM ($M2 = \exp[j2\pi n_2(x)]$) and the resulting image is again transformed by the FrFT with an order of β. In order to distribute the energy of the elemental images in an EIA, the Arnold transform (AT) algorithm is introduced in this encryption process. AT effectively solves the problem of energy proportion concentration of the elemental image. The encrypted image can be determined by the following equation:

$$\xi(x) = AT^{t}\left\{F^{\beta}\left\{\begin{array}{l} F^{\alpha}\left\{AT^{t}(f(x))\exp[j2\pi n_1(x)]\right\} \\ \exp[j2\pi n_2(x)] \end{array}\right\}\right\} \quad (6)$$

where $n_1(x)$ and $n_2(x)$ represent the two independent random matrices and AT^t represents the image that is scrambled by t times of AT.

2.3. EIA decoded by inverse FrFT

EIA decryption is an inverse process of encryption. The FrFT with an order of $-\beta$ is first performed on an encoded image; the transformed image is then multiplied by the conjugation of the RPM $M'2 = \exp[-j2\pi n_2(x)]$. Repeating the process using order $-\alpha$ and $M'1 = \exp[-j2\pi n_1(x)]$, the decrypted image can be determined from the following equation:

$$f(x) = AT^{T-t}\left\{F^{-\alpha}\left\{\begin{array}{l} F^{-\beta}\{(\xi(x)\exp[-j2\pi n_2(x)])\} \\ \exp[-j2\pi n_1(x)]) \end{array}\right\}\right\} \quad (7)$$

where T denotes the period of the AT transform

2.4. Double image reconstruction process

In CIIR, all elemental images are inversely magnified according to the magnification factor $M = l/g$ through a virtual pinhole array and added at the reconstructed output plane $z = l$, where l represents the distance between the reconstructed plane images and the virtual pinhole array, and g denotes the gap between EIA

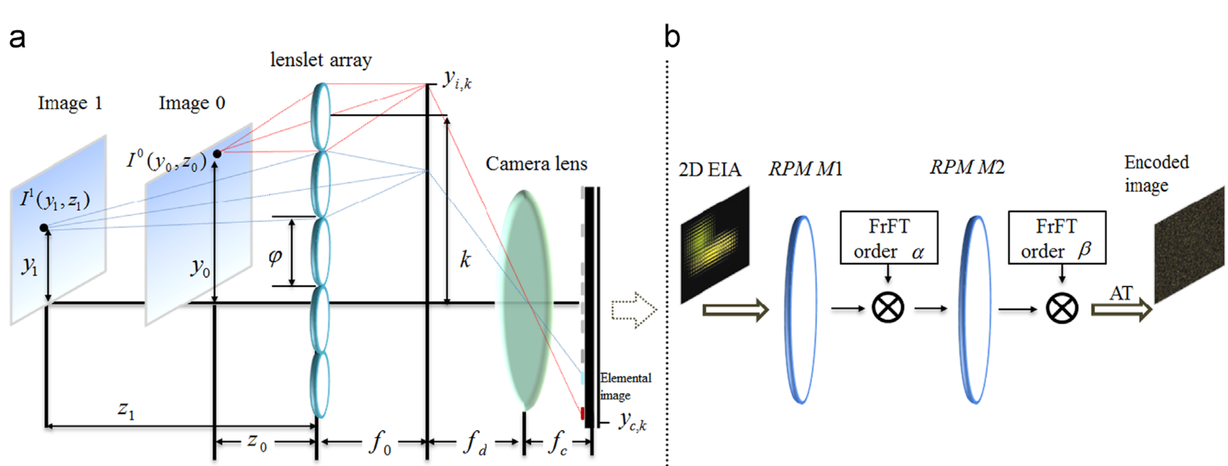

Fig. 1. Schematic of double images optical pickup and encryption: (a) pickup process, and (b) encoding process.