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Implementation of Image Encryption Using The Phase-Contrast Technique

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ABSTRACT

An image encoding scheme using the phase-contrast technique [7] and a random phase distribution [1] is proposed to encrypt images in phase masks. The robustness of the encoding is assured by the non-linearities intrinsic to the phase-contrast technique and the bandwidth of the random phase distribution. The advantage of this method, compared to the previous methods proposed [2,3], is the direct encoding of the image without any iterative calculation to generate the phase mask. This approach permits practical applications since the final phase mask could be implemented using thermoplastic plates [8] and spatial light modulators (SLM's) [5,6].

Keywords: Optical security; optical image encryption; phase-contrast technique; phase mask; thermoplastic plate, spatial light modulator (SLM).

1. INTRODUCTION

Previous works have proposed the use of random phase distributions [1] and Fourier (Fresnel) phase holograms to encrypt images in phase masks [2,3]. The encryption of a gray level image a_{mn} was achieved by multiplying the computer generate speckle-free phase hologram F_{mn} ($|F_{mn}|=1$) of a_{mn} by a random phase distribution $\exp[j2\pi b_{mn}]$, resulting in a encrypted phase mask $F^e_{mn} = F_{mn} \exp[j2\pi b_{mn}]$.

The encrypted phase mask could be bonded [4] to a credit card and serves as a device to verify the card authenticity. The authenticity is performed when the intensity of the gray level image a_{mn} could be optically recovered in the presence of a phase key $\exp[-j2\pi b_{mn}]$ modulated by a phase-only SLM [5,6]. When the phase only mask and the SLM are well aligned (the encrypted phase mask multiplies the phase key), the random phase present in the phase mask is canceled and the original image a_{mn} is recovered by the optical Fourier transform (free propagation). The advantages in use phase masks lies in the impossibility of duplicate the information of the phase distribution using common image replication methods. It's content cannot be determined by light intensity detectors and it is also impossible to recover the encrypted image a_{mn} by blind deconvolution, since the image is complex valued. Without knowing the key mask, one cannot decode the

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encrypted phase mask. Optical simulations [2,3] demonstrated that when the key is not present, the optical image reconstruction is indistinguishable.

The technique described above assures a robust encryption but it is extremely time consuming due to the iterative algorithm to generate the phase hologram. To avoid this problem, an image encryption scheme based in the Zernike [7] phase-contrast technique and a random phase distribution is proposed. The robustness of the encoding is assured by the non-linearities intrinsic to the phase-contrast method and the bandwidth of the random phase distribution. The advantage of this method, compared to the previous methods proposed [2,3], is the direct encoding of the image without any iterative calculation to generate the phase-only mask. The final phase-only mask could be implemented using thermoplastic plates and SLM's [5,6].

2. THE PHASE CONTRAST TECHNIQUE

The phase contrast technique is a well known microscope imaging technique [7] for converting a spatial phase modulation to a spatial intensity modulation. Suppose a transparent object $t_{mn} = \exp(j\phi_{mn})$ coherently illuminated in an image-forming system like the 4f optical correlator. A magnification of unity is assumed and the finite extent of the entrance and exit pupil is not considered. The phase shift ϕ_{mn} must be less than 1 radian as a necessary condition to achieve linearity [7]. Neglecting the terms of order ϕ^2_{mn} and higher, the amplitude transmittance can approximated by

$$t_{mn} \simeq 1 + j\phi_{mn} \tag{1}$$

The first term of equation (1) represent the light that passes through t_{mn} without change and the second term represent the diffracted light. The image produced by the system can be written

$$I_{mn} \simeq \left| 1 + j\phi_{mn} \right|^2 \simeq 1 \tag{2}$$

The diffracted light is not observed because it is in phase quadrature with the background. If this phase quadrature is modified using a phase-changing plate, intensity variations results and the transparent object could be observed. The phase-changing plate consist in a glass substrate with a small transparent dielectric dot coated in the center. The dot is placed in the center of the back focal plane of the first lens where we have the optical Fourier transform of the transparent object. The dot has a thickness and index of refraction suck that the phase of the zero order component of the Fourier transform is retarded by $\pi/2$ radians relative to the phase of the other orders. The inverse Fourier transform performed by the second lens gives the intensity of the resulted image:

$$I_{mn} \simeq \left| \exp\left[j\left(\pi/2\right)\right] + j\phi_{mn} \right|^2 \simeq 1 + 2\phi_{mn} \tag{3}$$

In equation (3) the image intensity has become linearly related to the phase shift ϕ_{mn}. It is also possible to improve the image contrast by making the phase-shift dot partially absorbing [7].

3. IMAGE ENCRYPTION USING THE PHASE-CONTRAST TECHNIQUE

Consider the transparent object t^a_{mn} generated from the normalized gray level image a^n_{mn} to be encrypted, shown in figure 1a:

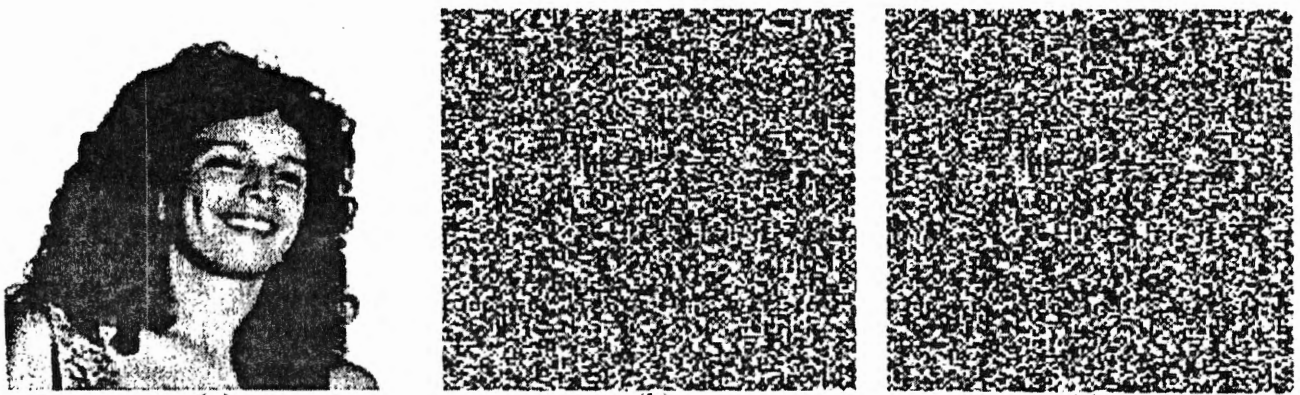
$$t^a_{mn} = \exp\left[ja^n_{mn}\right], \qquad 0 \le a^n_{mn} \le 1 \tag{4}$$

(the gray level image a^n_{mn} is normalized to a maximum value of 1 to assure the linearity condition). The encryption of the image a^n_{mn} is achieved by multiplying the transparent object t^a_{mn} by a random phase distribution $\exp[j2\pi b_{mn}]$ (figure 2b), resulting in a encrypted phase mask t^e_{mn}:

$$t^e_{mn} = \exp\left[j\left(a^n_{mn} + 2\pi\, b_{mn}\right)\right], \qquad 0 \le b_{mn} \le 1 \tag{5}$$

b_{mn} is a random white noise uniformly distributed in the interval [0,1]. The encrypted phase mask t^e_{mn} is shown in figure 1c.

The content of the phase mask t^e_{mn} cannot be determined by light intensity detectors and it is also extremely complex to recover the encrypted image a_{mn} by blind deconvolution, since the necessary condition to assure linearity between the phase shift and image intensity is not respected. If one tries to record the phase mask t^e_{mn} applying interferometric processes, a severe loss of information will occur due to the association of the finite aperture intrinsic to any optical system and the not band-limited random phase noise $\exp[j2\pi b_{mn}]$ in the phase mask t^e_{mn}. The recorded image will include such strong speckle noise that it becomes undistinguishable [2]. Without knowing the key mask $\exp[-j2\pi b_{mn}]$, one cannot decode the phase mask t^e_{mn}.



(a) (b) (c)

Figure 1: (a) The gray level image a_{mn} to be encrypted; (b) Random phase distribution $\exp[j2\pi b_{mn}]$, where b_{mn} is a random white noise uniformly distributed in the interval [0,1]; (c) The encryption of the image a_{mn} is achieved by multiplying the transparent object $t^a_{mn} = \exp[a^n_{mn}]$ by a random phase distribution $\exp[j2\pi b_{mn}]$, resulting in a encrypted phase mask t^e_{mn}. The gray level of figure 1b and 1c is linearly related to the phase value. The 0 gray-level value (black) corresponds to the phase value 0, the 255 gray-level value (white) correspond to the phase value 2π. Other gray level value corresponds to an intermediate value of phase.

Figure 2 suggests the scheme of a recording camera to store the encrypted phase mask t^e_{mn} on a thermoplastic plate [8] bonded on a card. The gray level image a_{mn} to be encrypted is recorded by a CCD camera and stored in the recording camera driver. A random white noise b_{mn} uniformly distributed in the interval [0,1] is generated from an initial number (seed) and added to the normalized distribution a^n_{mn}, resulting in the phase distribution

$$p^e_{mn} = a^n_{mn} + 2\pi b_{mn} \tag{6}$$

The phase distribution p^e_{mn} of equation 6 is recalculated to be in the interval $0\text{-}2\pi$, resulting in the phase distribution $p^{e\ 0\text{-}2\pi}_{mn}$. This distribution is converted to a gray level signal gl^e_{mn} varying from 0 to 255 using the relation

$$gl^e_{mn} = \frac{255}{2\pi}\left[\, p^{e\,0-2\pi}_{mn} \,\right] \tag{7}$$

The gray level signal drives a SLM in an amplitude modulation regime [6]. The pattern modulated by the SLM is transferred to the thermoplastic plate by an imaging system. The development of the thermoplastic plate by heating causes a permanent deformation on the surface, resulting in the desired phase modulation.

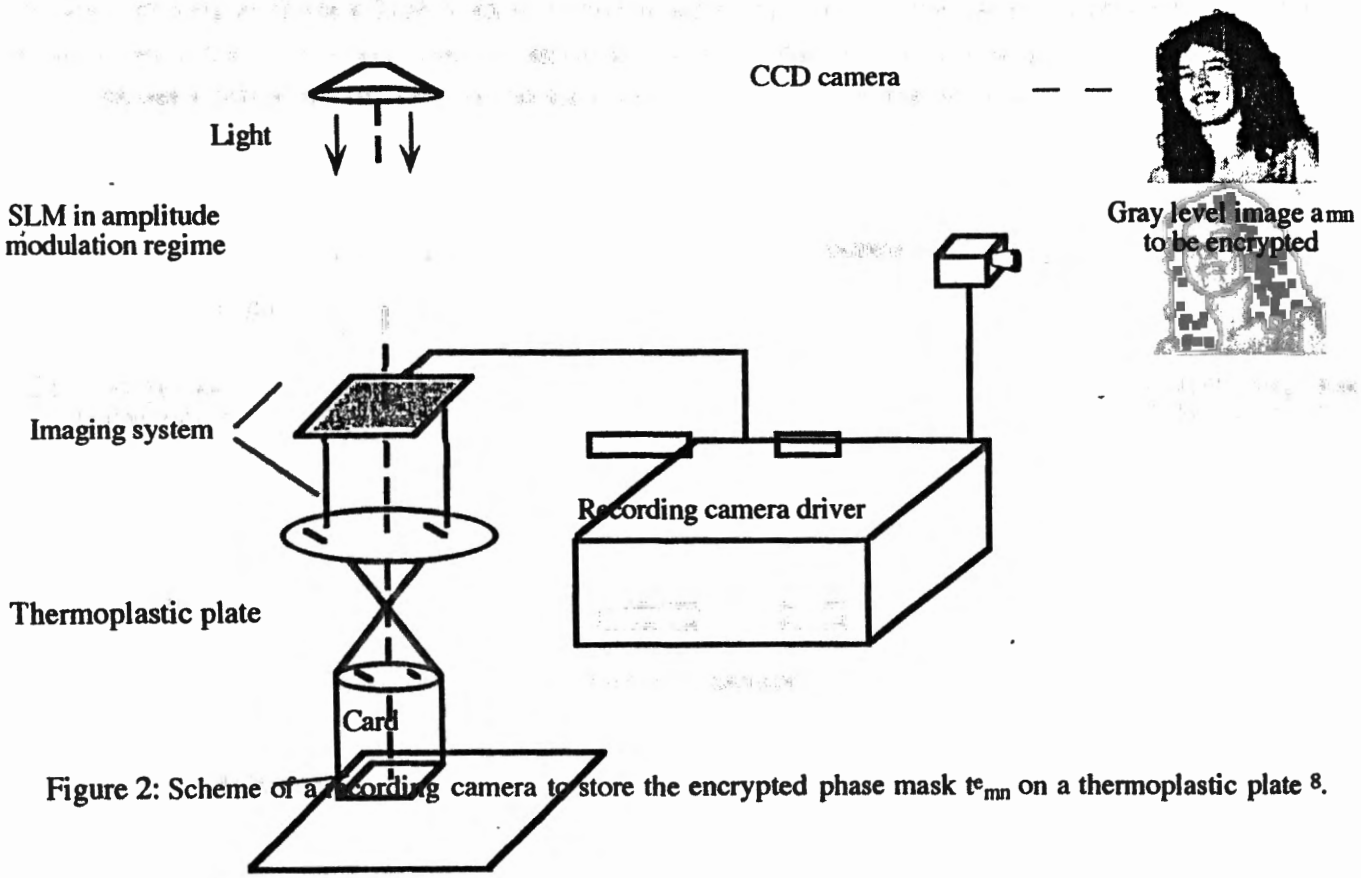


Figure 2: Scheme of a recording camera to store the encrypted phase mask t^e_{mn} on a thermoplastic plate [8].

4. IMAGE RECOVERING

The intensity of the encrypted image could be optically recovered by applying the phase contrast technique to the phase mask t^e_{mn} multiplied by the phase mask key $\exp[-j2\pi b_{mn}]$. Figure 3 shows the 4f optical correlator used to recover the encrypted image from the phase only mask. The phase mask t^e_{mn} is aligned to a SLM in phase modulation regime [5,6]. When the phase mask is multiplied by the phase key $\exp[-j2\pi b_{mn}]$ modulated by the SLM, the random phase term $\exp[j2\pi b_{mn}]$ stored in phase mask is canceled, resulting only the phase term $t^a_{mn} = \exp[\, ja^n_{mn}]$:

$$t^a_{mn} = \exp\left[j\left(a^n_{mn} + 2\pi\, b_{mn}\right)\right] . \exp\left[-j\,2\pi\, b_{mn}\right] = \exp\left[j\, a^n_{mn}\right] \qquad (8)$$

The intensity of the original image is optically recovered by applying the phase contrast technique as described in section 2.

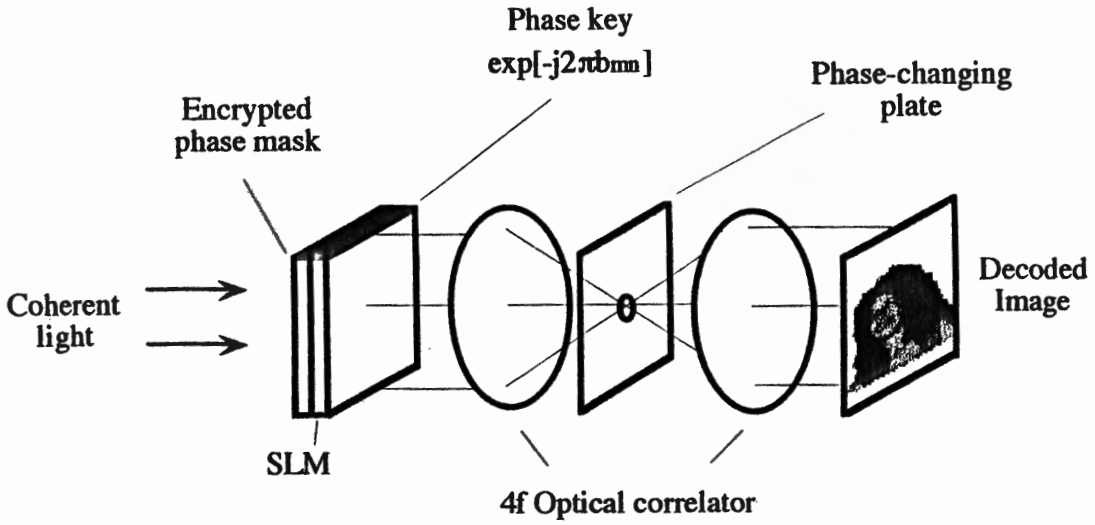
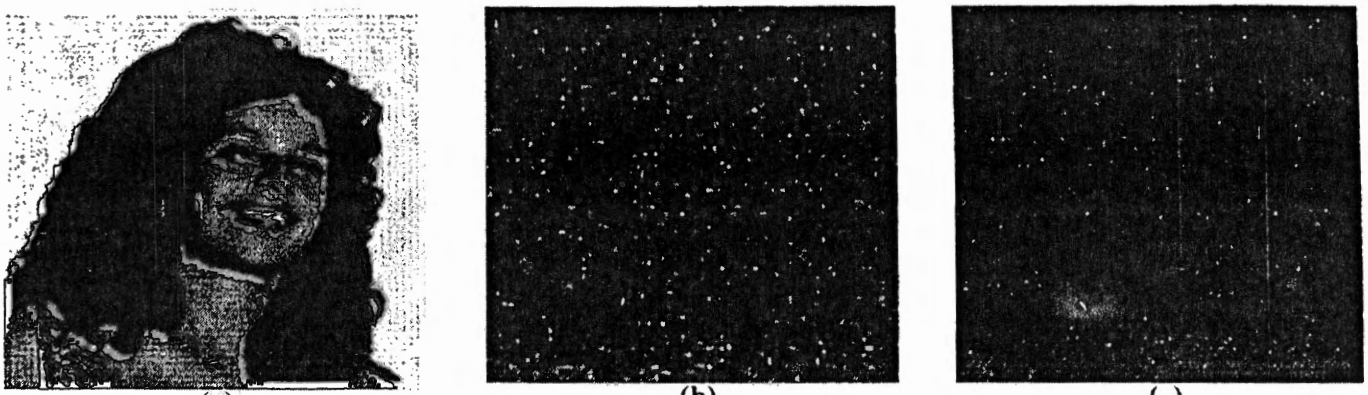


Figure 3: The 4f optical correlator system to recover the encrypted image from the phase only mask.

Figure 4a shows the computer simulations of the reconstruction of encrypted image when the phase-only mask t^e_{mn} of figure 2c is multiplied by the phase key $\exp[-j2\pi b_{mn}]$. The simulation considers the finite size of the phase-only mask in the input of the 4f correlator and the finite size of the phase-changing plate placed in the Fourier plane. This finite size introduces a sinc convolution in both planes, simulating an optical behavior. Figure 4b shows the reconstruction when the phase key is not present and figure 4c shows the reconstruction when the phase-only mask t^e_{mn} is multiplied by a wrong phase key. In both cases the reconstruction is indistinguishable. A critical point in the optical implementation of the system described in figure 3 is the alignment between phase mask t^e_{mn} and the SLM. This problem could be minimized by smoothing [2] the random phase distribution $\exp[j2\pi b_{mn}]$.



(a) (b) (c)

Figure 4: (a) Reconstruction of encoded image when the encrypted phase mask t^e_{mn} of figure 2c is multiplied by the phase key $\exp[-j2\pi b_{mn}]$; (b) Reconstruction when the phase key is not present; (c) Reconstruction when the encrypted phase mask t^e_{mn} is multiplied by a wrong key.

5. CONCLUSION

The phase contrast method is proposed as direct technique to encrypt an image in a phase-only mask. The thermoplastic plate is suggested as a media to store the resulted phase-only mask. The robustness of the encoding was assured by the non-linearities intrinsic to the phase-contrast method and the bandwidth of the random phase distribution.

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