Digital Holography for Recognition and Security of 3D Objects

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Abstract Three-dimensional (3D) object recognition has been achieved by comparing either holograms or the reconstructed images from respective holograms using conventional and nonlinear joint fractional transform correlators. For 3D information security, an encrypted image has been used as digital watermark. The encryption scheme is based on polarized light encoding and the photon counting technique. Multiple images may also be used as watermark. A multiple image encryption system has been proposed which is based on phase mask multiplexing and photon counting imaging.

1 Introduction

Digital holographic technique is used to record optical wavefront digitally and recreate the same wavefront optically or by numerical algorithms [1, 2]. The 3D object identification is an important area where digital holography is efficiently used [3–8]. Targets in 3D space cannot be identified by two-dimensional (2D) correlators because 2D correlators can't determine longitudinal distances accurately [8]. However, 2D correlators have been used to identify 3D objects using different perspectives of the object [8]. Many researchers have used joint fractional correlator (JFRTC) for 3D correlation [9–13]. The correlator's performance is improved by introducing nonlinearity in the joint power spectrum [11–13].

A fractional Fourier transform (FRT)-based scheme for 3D object recognition has been discussed [12, 13]. DH of different 3D objects are recorded numerically and reconstructed corresponding 3D images are compared with the reference object using JFRTC and nonlinear JFRTC [12]. These schemes are also verified by experimentally recorded digital hologram (DH). 3D correlation is also performed by comparing the holograms directly, since the holograms contain the complete

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information of the 3D object. A comparative study of the conventional and non-linear JFRTC for 3D recognition has been performed using both the methods of recognition of real 3D objects [13]. Various performance measure parameters have been computed to compare the strength of the proposed correlation schemes.

DHs may be used to store important data which needs to be secured. Hologram watermarking is an important technique to secure and prevent unauthorized copying of data [14]. In this technique, an image or a data is embedded in the digital media in a way which prohibits the image or a data from being accessed by unwarranted users and lets the image/data be read when needed. In many cases, encrypted images are used as watermark which offers additional level of security.

Over the years, researchers have developed various encryption schemes including double random phase encoding, phase truncation-based cryptosystem, interference-based image encryption, and multiple image encryption [14–21]. To add to the security of the encrypted image, photon counting imaging (PCI) technique has been clubbed with different encryption schemes [22–24]. An image encryption scheme has been discussed which is based on PCI technique and phase mask multiplexing for multiple image authentications [24]. The authentication scheme has also been used for securing 3D information contained in optically captured DH.

Another optical image security system utilizing the concept of polarized light encoding [25–30] and PCI technique has been briefly explained [30]. An input image is encoded using Stokes-Mueller formalism. The PCI technique is used to further encrypt the already encoded image. Attack analysis has also been carried out to check the robustness of the encryption scheme. The proposed encryption system has been used for 3D information security through hologram watermarking technique [31].

2 Three-Dimensional Correlation

2.1 3D Recognition with Digital Fresnel Hologram

The 3D correlation with the help of DH is realized because DH records different perspectives of a 3D object in different portions of a DH [4, 10]. The matching between the target 3D and given reference objects is performed by calculating correlation coefficient which is given by (1).

$$\mathrm{C}(x, y) = \Im^{-1}\left\{\Im^{\mu}\{\mathrm{H}_{\mathrm{tar}}(x, y;\ d;\ \alpha, \beta)\}\{\Im^{\mu}\{\mathrm{H}_{\mathrm{ref}}(x,\ y;\ d;\ \alpha', \beta')\}\}^{*}\right\} \tag{1}$$

$\Im^{\mu}$ and $\Im^{-1}$ denote fractional Fourier transform with order μ and inverse Fourier transform, respectively. $H_{\mathrm{tar}}(x, y; d; \alpha, \beta)$ and $H_{\mathrm{ref}}(x, y; d; \alpha', \beta')$, represent one perspective of the target and reference objects, respectively. $H(x, y; d; \alpha, \beta)$ denotes a region of the hologram which is used for recreating an angular view (α, β) of the 3D object and d represents the reconstruction distance.

2.2 Joint Fractional Fourier Transform Correlators

The conventional correlation scheme used for 3D correlation gives by Tripathi et al. [11],

$$C(x,y) = \Im^{-1}[\Im^{\mu}\{g(x,y)\} \times [\Im^{\mu}\{g_r(x,y)\}]^*] \tag{2}$$

Here, g(x, y) and $g_r(x, y)$ represent images of target and reference objects. Nonconventional nonlinear JFRTC is an extension of JFRTC in which joint fractional power spectrum is nonlinearly transformed using power-law transformation [11]. A high correlation coefficient means that the reference image is similar to the input target image. n is nonlinearity factor and is one for JFRTC. Mathematically, nonlinear JFRTC is represented as,

$$C(x,y) = \Im^{-1}\left[|\Im^{\mu}\{g(x,y)\} \times [\Im^{\mu}\{g_r(x,y)\}]^*|^n \times \exp\{i \arg[\Im^{\mu}\{g(x,y)\}] - \arg[\Im^{\mu}\{g_r(x,y)\}]\}\right]. \tag{3}$$

3 Hologram Watermarking

The DH is secured by embedding an encrypted image into a host image. The encrypted image is used as a watermark and recorded DH is considered as a host image. The process of hologram watermarking is defined as Rajput et al. [24],

$$I_w(\xi,\eta) = I(\xi,\eta) + aE_p(\xi,\eta) \tag{4}$$

where, a is an arbitrary constant. The original as well as watermarked hologram reconstruct the same 3D object. The original watermark, which is known only to the actual owner, is retrieved from the watermarked DH using (5).

$$E_p(\xi,\eta) = \frac{I_w(\xi,\eta) - I(\xi,\eta)}{a} \tag{5}$$

Now, the decrypted retrieved watermark is verified using nonlinear JFRTC. The authenticity of the original hologram is verified using the correlation peaks obtained using the correlator.

3.1 Multiple Image Encryption Using Photon Counting Imaging and Phase Mask Multiplexing

A novel multiple image encryption technique has been proposed which utilizes modified GS algorithm for phase-retrieval and phase mask multiplexing technique [24]. The multiple images are converted into their corresponding phase-only images (POIs) with the help of the GS algorithm and then a single phase mask is synthesized by multiplexing these POIs. The individual keys are generated for successful retrieval of original images from the single phase mask. Further, FRT operation is performed on the single phase mask and then it is multiplied with a random phase mask to obtain complex valued function. To further strengthen the security of the encryption scheme, PCI technique is used. The output image obtained from PCI technique has sparse representation because it has limited number of photons as compared to the number of incident photons. Authenticity of the multiple images are checked by decrypting the encrypted image at first with proper decryption process and then the photon limited decrypted and original images are compared by calculating the correlation coefficient using nonlinear JFRTC.

3.2 Encryption Scheme Based on Polarized Light Encoding and Photon Counting Imaging

The encryption scheme uses polarized light encoding with the help of Stokes-Mueller formalism and then PCI technique has been applied to further encrypt the image [30]. Two different waves have been used to illuminate the image which is to be encrypted and an intensity image which acts as encryption key. The two light waves are combined to obtain a multiplexed stokes vector. The obtained multiplexed stokes vector, is further encoded by the pixilated polarizer with randomly distributed angles whose values lie between $-\pi$ and $+\pi$. The PCI technique has been utilized to further encrypt the polarized light encoded image. For the purpose of authentication verification, we used nonlinear optical correlator. The correlation between original input image and photon limited decrypted image can be obtained.

4 Results and Discussions

4.1 3D Object Recognition

Recognition of 3D object is demonstrated numerically as well as experimentally. Figure 1a shows the target image and Fig. 1b shows the experimentally recorded

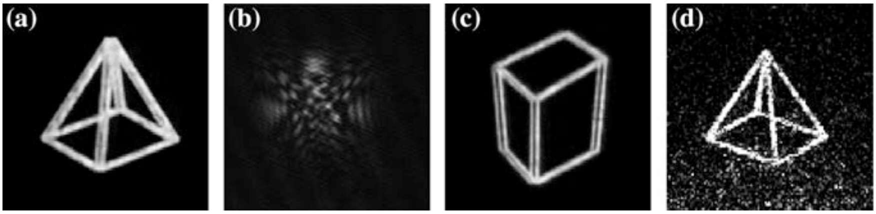

Fig. 1 **a** Pyramid, as the target object, **b** simulated DH for the pyramid, **c** rectangular prism, and **d** reconstructed pyramid [12]

DH. A rectangular prism, as shown in Fig. 1c, has been compared with the reconstructed pyramid image, shown in Fig. 1d. The JFRTC and nonlinear JFRTC have been used to obtain autocorrelation peaks between pyramid and the reconstructed pyramid. The cross-correlation between a rectangular prism and the reconstructed image of the pyramid is also obtained using JFRTC and nonlinear JFRTC. On comparing the correlation results, it is observed that nonlinear JFRTC discriminates between dissimilar objects better.

4.2 3D Correlation: A Comparative Study

The optical setup for recording DH of a real 3D object has been shown in Fig. 2. A He–Ne laser (make: Research Electro-Optics, USA) having 35 mW power and 632.8 nm wavelength has been used as a source of coherent light. Figure 3b, d show the recorded reference and target DHs, respectively. The numerically reconstructed 3D images have been shown in Fig. 3c, e. The two DHs and the two reconstructed 3D images have been compared with the help of JFRTC and nonlinear JFRTC. Performance measure parameters for the two correlation outputs have also been calculated to compare the conventional and nonlinear JFRTCs.

4.3 Hologram Watermarking

4.3.1 Phase Multiplexed Photon Limited Encrypted Image

Four different images each with size 256 × 256 pixels have been used for this study. The four gray-scale images have been shown in Fig. 3a–d. The multiplexed encrypted image, shown in Fig. 3e is obtained as a result of multiplexing of POIs obtained with the help of modified GS algorithm. The photon limited encrypted image has been shown in Fig. 3f. It is sparsely represented, therefore is indistinguishable. The auto-correlation peaks are obtained when the photon limited decrypted images obtained after using all correct keys, are compared with the

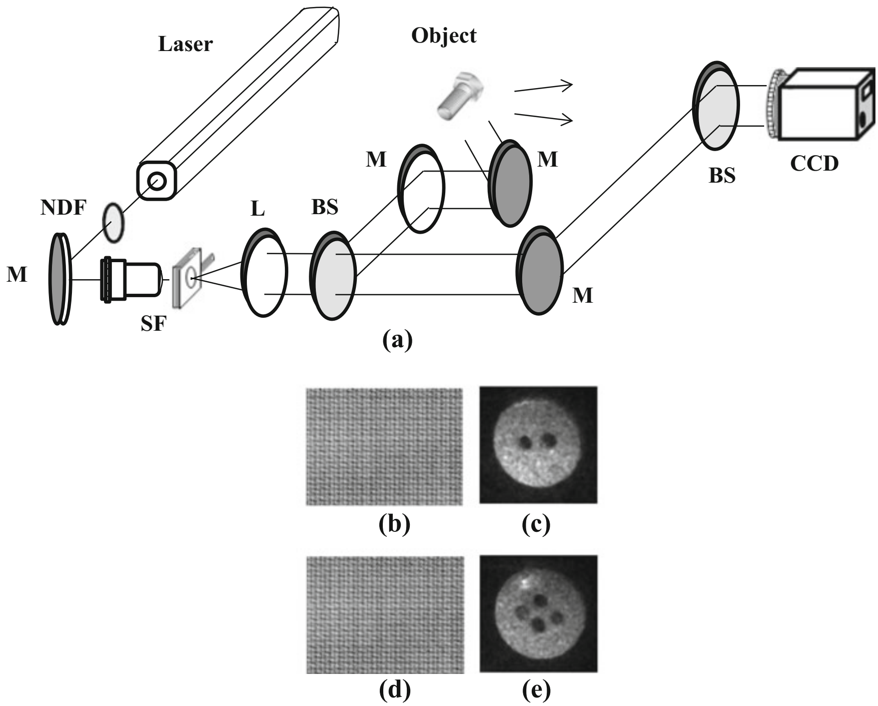

Fig. 2 **a** Experimental arrangement for recording DHs of 3D real objects. *M* Mirror, *BS* Beam Splitter, *L* Lens, *SF* Spatial Filter, and *NDF* Neutral Density Filter. **b** Reference hologram **c** reconstructed reference object **d** target hologram, and **e** reconstructed target object [13, 24]

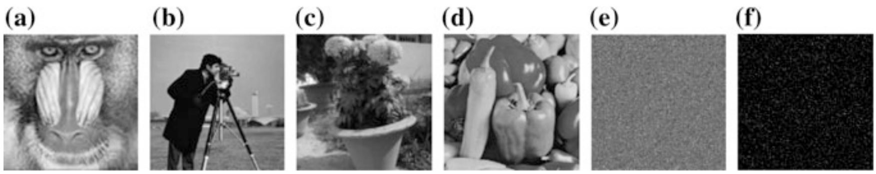

Fig. 3 Simulation results: gray images of a **a** Baboon, **b** Cameraman, **c** Flower pot, **d** Capsicum **e** phase multiplexed encrypted image, and **f** encrypted image obtained with PCI technique [24]

corresponding original. Experimentally recorded DH is watermarked with the sparsely represented encrypted image using PCI technique containing the information of multiple images in the photon limited domain. The watermarked hologram has the information of multiple images. Reconstruction of original and watermarked DHs gives same image of the real 3D object. Authenticity of the retrieved watermark has also been checked by comparing the original and the photon limited decrypted images.

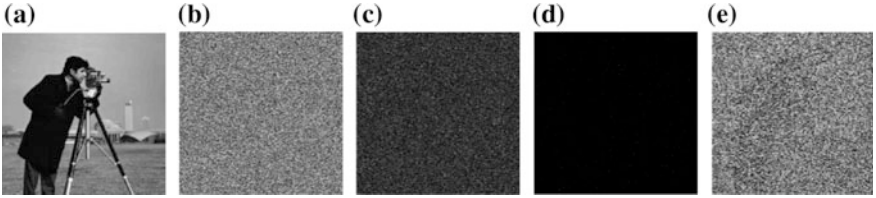

Fig. 4 Simulation results: **a** Cameraman, **b** intensity image, used as key, **c** polarized light encoded image, and **d** photon limited encrypted image, and **e** photon limited decrypted image [30]

4.3.2 Polarization-Encoded Photon Limited Encrypted Image

In Fig. 4a, a gray-scale image of a Cameraman having size 256 × 256 pixels has been used for encryption. Figure 4b, c, and d show the intensity image acting as encryption key, the polarization encoded image, and the sparsely represented encrypted image obtained on application of PCI technique, respectively. Figure 4e shows the decrypted image in photon limited domain.

Attack analysis has also been carried out to the verify robustness of the proposed encryption system. The photon limited encrypted image has been used for watermark. Reconstructed images from the original and the watermarked holograms are same, however the authenticity of the holograms can be checked with the help of retrieved watermark.

5 Conclusions

A comparative study of conventional JFRTC and nonlinear JFRTC has been done for real 3D object recognition. The study has been carried out by recording DHs numerically as well as experimentally. It is concluded from the study that the two slightly different 3D objects can be discriminate with nonlinear JFRTC better as compared to the conventional JFRTC. Security of the DHs is ensured by hologram watermarking with encrypted images. The encrypted images are obtained by multiple image phase multiplexing and PCI technique. Another encrypted image used for hologram watermarking is obtained by polarized light encoding and PCI technique.

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