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Statistical detection of digital holographic watermarking system

Li-Chien Lin [a,*], Chiung-Liang Chen [b]

[a] Department of Communications Engineering, Feng Chia University, Taichung, Taiwan, ROC
[b] The Graduate Institute of Electrical and Communications Engineering, Feng Chia University, Taichung, Taiwan, ROC

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ABSTRACT

In this paper, we examine the statistical properties of the holographic watermarking system [C.J. Cheng, L.C. Lin, W.T. Dai, Opt. Commun. 248 (2005) 105] and facilitate a systematic way to determine an optimal threshold of the correlation signal for detecting the authorized mark pattern. The holographic watermarking system constructs a digital holographic watermark using modified Mach–Zehnder interferometric architecture, and the correlation signal is obtained using an optical VanderLugt 4-f correlator to identify the authorized mark in the watermarked image. To obtain the best detection performance, we use statistical modeling of the entire holographic watermarking system. Accordingly, we derive correlation signal statistics and hypothesis testing to obtain an optimal threshold for the watermark detector that minimizes the detection error. The theoretical result of this paper allows us to easily determine an optimal threshold and evaluate the robustness of the watermark detector. The robustness of the proposed optimal detector is evaluated using detection error, and detection performance is demonstrated by simulation experiments.

1. Introduction

The success of internet and technological advances in wired and wireless networks has made it easy to create, duplicate, transmit, and distribute digital content. Concurrently, the protection and enforcement of intellectual property rights for digital content has become increasingly important. A leading technological solution has been watermarking systems. A watermarking system provides a way to embed an authorized watermark in such a way that it does not affect the perceptual quality of the underlying cover image. The watermark should be difficult to remove or detect by an unauthorized user even if the exact watermarking algorithm is known. Recently, optical watermarking techniques have been of increasing interest in the optical processing community since the techniques provide multiple encoding methods to protect data in parallel processing architecture.

Kishk and Javidi [2] proposed using the double random phase to encode a mark pattern into a Gaussian white noise image before embedding it into a cover image. Takai and Mifune [3] proposed a holography technique to create digital watermarks, in which a diffuse-type Fourier hologram is used to record the mark image. Advanced research [4] superimposed a digital holographic watermark onto the discrete-cosine-transform domain of the cover image to increase the robustness to low-pass filtering and additive Gaussian noise. The optical holographic technique has the advantage of encoding 3D object information into a complex function. More recent approaches [5–9] employed the phase-shifting interference technique to record the complex function and applied it to watermarking 3D objects using a hybrid optical/digital scheme.

In previous works [1], we proposed a correlation-based optical watermarking scheme using the digital holographic technique. The proposed system constructs a watermark using an optical holographic technique, the mark image is modulated using a random-phase diffuser and is Fourier transformed before the watermark is embedded into a cover image. To identify the authorized mark, the watermarked image is displayed on a nonlinear spatial light modulator (SLM) and used as a transmitted mask in the Fourier domain of an optical VanderLugt 4-f correlator. The first-order correlation signal of this correlator can be used to identify whether the authorized mark appears in the watermarked image. In digital watermarking, most articles consider the Log-likelihood detector to be an optimal detector, when the cover image does not follow a Gaussian pdf or when the watermark embedding is not additive. However, the correlation detector is used here, since the watermark detection can be practically implemented by an optical correlator. The remarkable feature of this watermarking system is that it performs both the construction and detection of the holographic watermarks by optical processing to fully utilize the processing power of light. Other than the digital watermarking system, which identifies the watermark using pixel-wise processing, the proposed optical watermarking system can detect hidden marks by one pass

* Corresponding author. Tel.: +886 424517250.
E-mail address: lclin@fcu.edu.tw (L.-C. Lin).

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of the light wave through an optical 4-f correlator; it should require less than one microsecond.

Nearly all relevant research provides optical methods to encode mark information into a pseudorandom pattern and implement a watermarking system. However, few studies [5,7] provide a systematic way to analyze system performance. To obtain the best performance, reliable detection must be investigated. The major objective of this paper is to derive a mathematical model of the proposed optical watermarking system, and to analyze the statistical property of this system. Since the watermark detection consists of the nonlinear optical SLM device, the power-law function is used to model the nonlinear characteristic of the watermark system. By the derivation, the resultant correlation signal can be viewed as a random variable with normal distribution, and the summary statistics are evaluated. Then, hypothesis testing is used to derive an optimal correlation threshold, which is obtained by minimizing the detection error. As a result, a reliable watermark detector can be applied to identify whether the authorized mark appears in the watermarked image. The reliability of watermark detector is evaluated using the total probability, defined as the sum of false alarm and missed detection probabilities. It is important to notify that the purpose of this paper is to derive a statistical model to select an optimal threshold for the proposed holographic watermarking system; it is not to find an optimal decoder. Our detector is already defined as a correlation detector.

2. Optical watermarking system

The optical scheme, illustrated in Fig. 1, can be used to implement the correlation-based watermarking system, which consists of three basic procedures: watermark construction, embedding, and correlation detection. To construct the watermark, a holographic technique is employed to encode the mark pattern into an interference noise pattern, which is then used as a random watermark. The embedding process simply adds the weighted watermark to the cover image in an imperceptible way. The correlation-based detection is a robust and reliable way to determine the presence of the watermark in a given image, and it is suitable to implement the correlation in an optical information process. Thus, our previous research [1] proposed an optical correlator to detect the watermark.

2.1. Holographic watermark construction system

Let $f_m(x,y)$ and $\exp[j\phi(x,y)]$ be the mark pattern and the random-phase diffuser in the spatial domain, respectively, where the 2D phase $\phi(x,y)$ is an i.i.d. white noise random process uniformly distributed on $[-\pi,\pi]$. Then, the random-phase-modulated mark image and its Fourier transform are denoted $f(x,y) = f_m(x,y)\exp[j\phi(x,y)]$ and $F(\xi,\eta)$, respectively, which are obtained by the optical process as shown in Fig. 1.

Let $\varepsilon^2 = \sum_{x=0}^{N-1}\sum_{y=0}^{N-1} f_m^2(x,y)$ be the pass energy of the mark image; then the real and imaginary parts of $F(\xi,\eta)$ are independent Gaussian random processes with mean zero and variance $\sigma_F^2 = (\frac{1}{\sqrt{2}}\varepsilon)^2$. As a consequence, the envelope $|F(\xi,\eta)|$ is the Rayleigh distribution with mean $\mu_{|F|} = \sqrt{\pi/2}\sigma_F$ and variance $\sigma_{|F|}^2 = (2-\frac{\pi}{2})\sigma_F^2$, and the phase function $\phi_F(\xi,\eta)$ is a white noise random process uniformly distributed on $[-\pi,\pi]$. The nonzero-order Fourier-transformed hologram is obtained by the interference of two mutually coherent amplitudes, which are the Fourier-transformed watermark $F(\xi,\eta)$ and a tilted plane reference wave $R(\xi,\eta) = |R(\xi,\eta)|\exp[j(2\pi a\xi)]$. It can be written as:

$$W(\xi,\eta) = F^*(\xi,\eta)R(\xi,\eta) + F(\xi,\eta)R^*(\xi,\eta), \tag{1}$$

where the superscript * represents the complex conjugate and the spatial frequency a denotes the inclination of the plane wave in the ξ-direction, i.e. $a = \sin\theta/\lambda$. Here we assume that the amplitude of the reference wave $|R(\xi,\eta)|$ is unity, the watermark is then given by $W(\xi,\eta) = 2\alpha|F(\xi,\eta)|\cos[2\pi a\xi - \phi_F(\xi,\eta)]$.

Since $F(\xi,\eta) = |F(\xi,\eta)|\exp\{j\phi_F\}$ is a complex white noise random process, the nonzero-order digital hologram is also white noise with expected value:

$$\begin{aligned}\mu_W = E\{W\} &= E\{2|F(\xi,\eta)|\cos[2\pi a\xi - \phi_F(\xi,\eta)]\}\\ &= 2E\{|F(\xi,\eta)|\}E\{\cos[2\pi a\xi - \phi_F(\xi,\eta)]\} = 0,\end{aligned} \tag{2}$$

since the random-phase $\phi_F(\xi,\eta)$ is uniformly distributed over $[-\pi,\pi]$. Here $E\{\cdot\}$ denotes the expected value operator. Similarly, we can derive the variance:

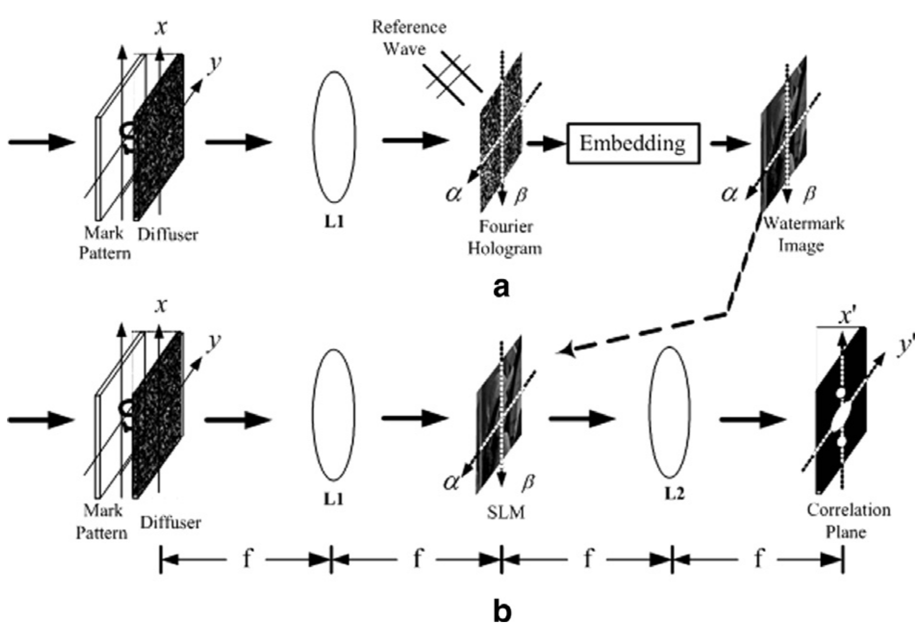

Fig. 1. Correlation-based watermarking system.