Implementation of a Nonzero-order Joint Transform Correlator Using Interferometric Technique

Chau-Jern CHEN1 and Han-Yen TU2

1Department of Electro-Optical Engineering, National Taipei University of Technology, Taipei 106, Taiwan, R.O.C.
2Department of Electronic Engineering, St. John’s & St. Mary’s Institute of Technology, Taipei 25135, Taiwan, R.O.C.

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The implementation of a nonzero-order joint transform correlator using the double port Mach–Zehnder interferometric technique is proposed and demonstrated. This approach provides on-line processing for directly removing the zero-order components of a joint power spectrum in one step and performs the nonzero-order optical correlation. Experimental results are presented and discussed.

Key words: joint transform correlator, optical pattern recognition, Mach–Zehnder interferometer

1. Introduction

The joint transform correlator (JTC) is an attractive approach to realize real-time optical pattern recognition because it can perform the correlation of two images without the use of a complex filter in the frequency domain, as needed with the VanderLught correlator. However, the classical JTC has been found to suffer from poor correlation discrimination ability, large correlation sidelobes, a strong zero-order peak with wideband which shares the available space-bandwidth product at the output plane and may suppress the valuable first-order correlation peaks, particularly for multi-target detection and noisy background conditions. To alleviate the problems of the classical JTC, many modified JTC architectures have been proposed.

Recently, Lu et al. proposed a nonzero-order joint transform correlator (NOJTC) using a phase-shifting technique, which uses the phase difference between reference and target to eliminate the zero-order spectra, or more recently using the iterative subtraction method of the spectrum removal in a computer. However, the removal of the zero-order spectra involves two or more steps in preprocessing of the input objects and time-multiplexing of the iterative process. That may cause detriment to the parallelism and pose limitations on high-speed processing applications. In this paper, the nonzero-order joint transform correlation based on the double port Mach–Zehnder interferometric technique is proposed and demonstrated. This approach offers the possibility of directly implementing the removal of the zero-order spectra in one step and extracting cosine wave information of the joint power spectrum, which yields the nonzero-order correlation, and it does not require storage of the Fourier spectra of either reference or target in a computer for the consecutive processes.

2. Interferometric Technique for Removing Zero-order Spectrum

The conceptual diagram shown in Fig. 1 consists of a double port Mach–Zehnder interferometer and an electronic subtractor (ES) and is used for the removal of the zero-order Fourier spectra (i.e., autocorrelation power spectra). Let $r$ and $t$ be the reflection and transmission coefficients of the beamsplitter (BS) for light incident from port 1, and $r'$ and $t'$ be the corresponding values when light is incident from port 2. The lenses L1 and L2 are placed directly against the beamsplitter and the focal length is hypothetically much larger than the thickness of the beamsplitter. Assume that the target at port 1 is coherently illuminated and Fourier optically transformed by lens L1. Passing through the beamsplitter, the irradiance of the transmitted and reflected Fourier spectra are respectively detected by a pair of photodetectors (CCD1 and CCD2) in the frequency planes (P1 and P2). Similarly, the reference at port 2 is Fourier optically transformed by lens L2, and thus the splitting Fourier spectra are also detected by the same CCD pair. Hence, the resultant spectra of both target and reference are jointed and superposed on CCD1 and CCD2. Subsequently, by sending the twin output signals of the CCD pair to an electronic subtractor (ES), we obtain the difference of the jointed power spectra of target and reference from the two ports. For simplicity, we consider the target $s_1(x - x_0, y)$ is off axis at port 1 and the reference $s_2(x, y)$ located on axis at port 2, where $(x, y)$ denotes the coordinate of input planes. Then, on the frequency plane P1, the transmitted components of Fourier spectrum of the target are

$$E_{1t}(u, v) = |t_1(u, v)| e^{-j2\pi xu_y} e^{j\phi_1(u, v)}$$

and the reflected components of Fourier spectrum of the reference are
\[ E_1(u, v) = r |S_1(u, v)| e^{j\phi_1(u, v)} \]

(2)

where \(|S_1(u, v)|\) and \(|S_2(u, v)|\) are the modules of the Fourier spectrum of target and reference, respectively, and \(\phi_1(u, v)\) and \(\phi_2(u, v)\) are the corresponding phases of the Fourier spectra. \((u, v)\) is the frequency coordinate at CCD plane. The two spectra of both target and reference are superposed and summed. The joint Fourier spectrum in the frequency plane

\[ I_1(u, v) = |E_1(u, v)|^2 = r^2 |S_1(u, v)|^2 + r^2 |S_2(u, v)|^2 + r|r| e^{j\phi_1(u, v)} \]

(3)

Similarly, the joint Fourier power spectrum in the frequency plane \((P2)\) is also obtained by CCD2 and written as

\[ I_2(u, v) = r^2 |S_1(u, v)|^2 + r^2 |S_2(u, v)|^2 + r|r| e^{j\phi_2(u, v)} \]

(4)

The outputs of the CCD1 and CCD2 are connected to an electronic subtractor and used as differential inputs, and thus the resultant output of the subtractor becomes

\[ I_S = I_2 - I_1 = (r^2 - r^2) |S_1(u, v)|^2 + (r^2 - r^2) |S_2(u, v)|^2 + [r|r| - r|r|] e^{j\phi_1(u, v)} \]

(5)

in which \(I_S\) denotes the difference of joint Fourier power spectrum between port 1 and 2. Using the Stokes relationships \((r^2 + r^2 = 0\) and \(r = r)\)

\[ I_S = (r^2 - r^2) |S_1(u, v)|^2 + (r^2 - r^2) |S_2(u, v)|^2 + 4 |S_1(u, v)||S_2(u, v)| e^{j\phi_1(u, v)} \]

(6)

where \(Re\{\cdot\}\) takes the real part. Assume that the beamsplitter is 50/50 (i.e., \(|r| = |t| = |r| = |t| = 1/2\), by substituting it into Eq. (7), then we obtain the difference of joint power spectrum as the following

\[ I_S = |S_1(u, v)||S_2(u, v)| \cos[2\pi u + \phi_1(u, v) - \phi_2(u, v)] \]

(7)

In Eq. (8) the difference signal \(I_S\) acts as a nonzero-order joint power spectrum (N0JPS) because the zero-order spectra \(|S_1(u, v)|^2\) and \(|S_2(u, v)|^2\) have been removed. The difference spectrum \(I_S\) extracts the cosine wave information from the joint Fourier spectrum and represents an amplitude modulated sinusoidal grating, which will produce the first-order diffraction correlation after further Fourier transformation. Hence, the N0JPS is inversely Fourier transformed and only cross-correlation terms will appear in the output correlation plane as

\[ C(x, y) = s_1(x, y) \otimes s_2(x, y) \oplus \delta(x - x_0, y) + s_2(x, y) \oplus s_1(x, y) \oplus \delta(x + x_0, y) \]

(8)

where the symbols \(\otimes\) and \(\oplus\) denote correlation and convolution, respectively, and \(\delta(x, y)\) is the Dirac delta function. As Eq. (9) indicates that the first-order diffraction terms at \((x \pm x_0, y)\) will produce two cross-correlations and the auto-correlation terms at the center have been eliminated, the output \(C(x, y)\) achieves the nonzero-order joint transform correlation.

3. Optical Experiments

The optical experimental setup of the nonzero-order joint transform correlator is shown in Fig. 2; it consists of a double port Mach–Zehnder interferometer and a SLM-based Fourier transform processor. The former apparatus is used for the removal of the zero-order terms of joint power spectrum, and the latter performs optical Fourier transformation and thus accomplishes the optical correlation. The optical system is linked by a personal computer for on-line processing. In the experiment, a He–Ne laser was used as

![Fig. 2. Experimental setup of the nonzero-order joint transform correlator.](image-url)