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Integrated zigzag Vander Lugt correlators incorporating an optimal trade-off synthetic discriminant filter for invariant pattern recognition

Ping Xu, Chunquan Hong, Zhilong Sun, Feng Han, Guanxiao Cheng*

Institute of Micro–Nano Photoelectronic Technology, College of Electronic Science and Technology, Shenzhen University, Shenzhen, Guangdong 518061, China

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ABSTRACT

Optical correlators (OCs) have a wide range of applications in the field of pattern recognition. We present a type of integrated zigzag Vander Lugt correlator (IZVLC). The IZVLC incorporates two Fourier transform lenses and one spatial light modulator (SLM) as a programmable filter, which can effectively miniaturize the volume of OCs and hence achieve better optical pattern recognition. In order to precisely recognize distortion targets, an optimal trade-off synthetic discriminant filter (OTSDF) is programmed on the SLM of the IZVLC. Both the simulative and experimental results have shown that the IZVLC can effectively identify distortion targets within a rotation angle of $\pm\pi/3$ and a scaling range of 0.6–1.6.

1. Introduction

Optical correlators (OCs) invented in the mid-1960s have been widely used in pattern recognition applications, such as satellite photograph analysis, to compare two-dimensional image data at very high speeds [1–6]. There are mainly two types of OCs: the Vander Lugt correlator (VLC) and the joint transform correlator (JTC). Both types achieve largely the same results, but process the information in different ways. The VLC, invented by Vander Lugt in 1964, is the most commonly used type of correlator, but also the most complex and sensitive to build, owing to its strict alignment criteria and long optical train. The advantages of VLC are a high space-bandwidth product and extremely fast process time. The JTC invented by Weaver and Goodman in 1966 differs significantly from the VLC process, since no reference filter is required. The advantages of JTC method are the simplified optical train and no strict alignment criteria.

Typically, image data entered into the OCs is compared during the correlation process in terms of two criteria: similarity and relative position. The comparison is generally done between a reference image from a database and an input image from an external camera or sensor. The optical output consists of highly localized intensities known as correlation spots or peaks. The intensity of the spots provides a measure of the similarity of the images being compared, whilst the position of the spots in the output denotes how the images are relatively aligned in the input scene. Multiple images may be also compared during the same process at no extra cost, limited only by the input resolution of the OCs. The OCs technique, however, suffers from certain deficiencies that are too sensitive to scale size changes and rotations of input patterns. When an input pattern is presented with an angular orientation or a scale size that is different from that of the pattern to which the filter is matched, the response of the correct matched filter is reduced, and errors arise in the pattern recognition process. There are a vast number of different pattern-recognition approaches that are aimed at reducing or eliminating sensitivity to extraneous parameters, such as scale size and rotation. One approach to handling patterns with different scale sizes and rotations is to synthesize a matched filter for an object of fixed size and rotation, and to perform a mechanical search, rotating and magnifying or demagnifying the input to the system. Mechanical searches, however, are awkward and time-consuming.

Therefore, more and more scientists are dedicated in developing function-integrated OCs with smaller volume and higher ability in invariant pattern recognition [1–6]. With recent advances in micro-optics technology, OCs coupled with spatial light modulators (SLMs) have become more flexible and more commercially viable. In this paper, based on the micro-optics technology developed in our lab [7–12], we will present one approach for achieving scale and rotation invariances that would lead to less time-consuming and higher-performance. The approach to invariant pattern recognition is through the use of a type of integrated zigzag Vander Lugt correlator (IZVLC) and an optimal trade-off synthetic discriminant filter (OTSDF) [13–15] programmed on an SLM of the IZVLC. The method provides a useful design procedure to obtain filters with a significant degree

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* Corresponding author. Tel.: +86 755 26557246.
E-mail address: gx.cheng@szu.edu.cn (G. Cheng).

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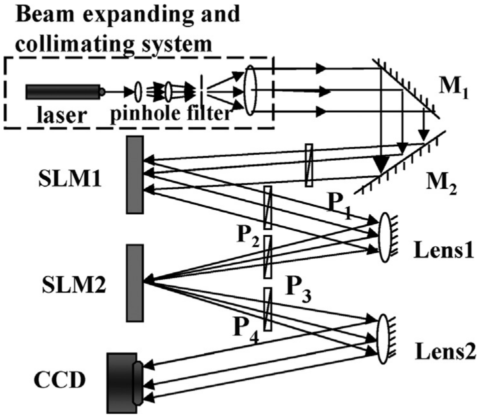

Fig. 1. Integrated optical module of the IZVLC: P1,P2, P3 and P4 are polarizers; Lens1 and Lens2 are reflective Fourier transform lenses; and M1 and M2 are plane mirrors.

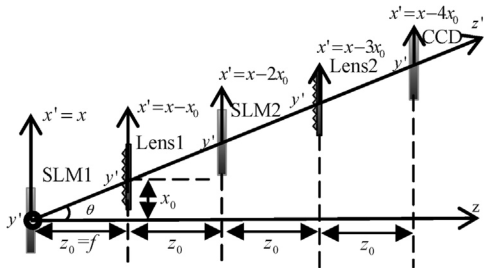

Fig. 2. Unfolded configuration shown in Fig. 1.

of invariance to various image parameters and without constraints of alignment.

2. Optical model of IZVLC

We present an integrated optical module of IZVLC which can be fabricated by micro-optics technologies to replace discrete components in the traditional 4f optical setup. The module is to fold the optical signal along a zigzag path which bounces between the two surfaces of a planar substrate as indicated in Fig. 1. The substrate can be a homogeneous block of quartz glass. The optical components, such as lenses, mirrors, filters and detectors, are distributed over both surfaces of the substrate. To simplify the fabrication as much as possible it would be an advantage to have alignment-critical components only on one side of the substrate and on the other side only components whose function is shift-invariant.

For convenience, we consider the unfolded version shown in Fig. 2. Elements are located in planes x–y perpendicular to the z direction. They are centered around an optical axis z' that deviates from the z axis by an angle θ. The lateral shift from the z axis to the oblique optical axis z' in a certain plane parallel to the x–y plane can be described by a number x_0. The focal length of the lenses is f.

We now apply the IZVLC model to the case of paraxial wave propagation along a tilted optical axis shown in Fig. 2. In general, the light propagation along a tilted optical axis, such as from the SLM1 surface to the front surface of DOE, can be written in terms of the point-spread function $h(x',y')$ of free space as follows [16]:

$$h(x',y') = \frac{\cos^2\theta}{i\lambda z_0}\exp\left[\frac{i2\pi z_0}{\lambda\cos\theta} + \frac{i\pi\cos\theta}{\lambda z_0}(x'^2\cos^2\theta + y'^2)\right] \qquad (1)$$

Parabolic lenses [16,17] can be used to compensate the inherent astigmatism of free-space propagation along a tilted optical axis limited in the planar optical system of IZVLC. The transmission function of the lens $L(x',y')$ is given by

$$L(x',y') = \exp\left[-\frac{i\pi\cos\theta}{\lambda f}(x'^2\cos^2\theta + y'^2)\right] \qquad (2)$$

Because of the Huygens–Fresnel principle, amplitude u in a certain plane z' can be calculated from the initial amplitude u_0 by a convolution with the point-spread function (see Eq. (1)) of free space. The output $O(x',y')$ of the IZVLC can be written as follows:

$$\begin{aligned} O(x',y') = {} & I(x',y') * h(x',y') L(x',y') * h(x',y') \\ & \times H(\mu,\nu) * h(x',y') L(x',y') * h(x',y') \end{aligned} \qquad (3)$$

where "$*$" is the convolution operation, $I(x',y')$ is the input image, and $H(\mu,\nu)$ is the matched filter.

3. OTSDF filter design

An OTSDF filter is designed to offer good performance in the distortion tolerance while maintaining relatively sharp correlation peaks for easily detecting the output of IZVLC. There are four key indicators for OTSDF: the average correlation energy (ACE), the output noise variance (ONV), the average similarity measurement (ASM) and the average correlation height (ACH). The basic idea of the OTSDF filter is to increase the ACH and to achieve a compromise between reducing the ASM, ACE and ONV by minimizing the following energy function:

$$\begin{aligned} E(f) &= \alpha(ONV) + \beta(ACE) + \gamma(ASM) - \delta(ACH) \\ &= \alpha f^{+} N f + \beta f^{+} C_x f + \gamma f^{+} S_x f - \delta |f^{T} p_x| \end{aligned} \qquad (4)$$

Consider a training set consisting of N sample images; the ith training image is $x_i(m,n)$, where each image contains $m \times n$ pixels, and total number of pixels is $d = m \times n$. The Fourier transform of each training image is reordered into a $d \times 1$ column vector r_i.

The average output power spectrum matrix C_x and the similarity matrix S_x can be illustrated as follows:

$$C_x = \frac{1}{N}\sum_{i=1}^{N} X_i X_i^{+} \qquad (5)$$

$$S_x = \frac{1}{N}\sum_{i=1}^{N} (X_i - M)^{+}(X_i - M) \qquad (6)$$

where "$+$" is the conjugate transpose operation, and X_i is a diagonal matrix whose diagonal elements are the training images vector r_i. Diagonal matrix M elements are the average vectors of training samples p_x. And p_x is the mean of the training images vector r_i.

A pure phase OTSDF filtering function can be written as follows:

$$h = Angle\left[\frac{p_x}{\alpha N_x + \beta C_x + \gamma S_x}\right] \qquad (7)$$

The operation *Angle* represents taken multiplexing angle of the complex filter. N_x is the noise power spectrum of images, and α, β, and γ are non-negative optimization parameters. Range $d \times 1$ column vector h can yield $m \times n$ matched filter $H(\mu,\nu)$. In practical applications, we can set the parameters α, β, and γ appropriately to improve the performance of the filter in a particular aspect. For example, setting $\alpha = \gamma = 0$, we will get a filter that has a similar performance to that of MACE [18] filter, with a sharp and anti-noise correlation peak, but sensitive to target distortion; setting $\beta = \gamma = 0$, we will get a filter that has a similar performance to that of MVSDF [19] filter, in which noise can be effectively filtered off, but the