Experimental investigation of a real-time nonlinear joint transform correlator

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Abstract. A hybrid digital-optical joint transform correlator has been built for recognition of objects with noise and multiple objects. The correlator uses two optically addressed LCLVs as input transducer and for intensity-recording the joint transform spectrum, two optical lenses for performing a Fourier transform, a CCD camera as active output transducer, and a digital system for postprocessing the output signal and refreshing the reference image through our object library. In our experiment, the spatially separated images are imaged onto one light valve, whose output is written on the second light valve. The output of the second light valve is optically processed to produce a correlation signal at the output transducer. The correlator is supported by a digital system so that the output can be digitized for further processing. Some experimental results for multiple-object recognition are presented and discussed.

Subject terms: pattern recognition; joint transform correlator.

Optical Engineering 33(10), 3302-3306 (October 1994).

1 Introduction

In recent years, the joint transform correlator (JTC) has been intensively developed. It has wide applications in image preprocessing, pattern recognition, information assessment, missile guidance, product-line inspection, and elsewhere.[1-3] It is different from the Vander Lugt correlator in that the object image and reference image in the JTC are input into a correlator to perform the Fourier transform at the same time. So the JTC can eliminate the need for off-line processing and for precision alignment, and it is unnecessary to prepare a matched spatial filter (MSF) in advance. In particular, by using a real-time device such as a liquid crystal light valve (LCLV) in the input plane and the FT plane of the JTC, a real-time correlation process can be achieved. Recently, the rapid development of devices such as the spatial light modulator (SLM) and charged-coupled device (CCD) have greatly advanced the development of JTC architecture.

The joint transform correlator is a good approach to optical pattern recognition. Our work has demonstrated that a real-time JTC can be implemented using two optically addressed LCLVs, a CCD camera, and a digital system. In this paper, some results of our experiments are given and the capability of the JTC for pattern recognition is analyzed.

2 The Basic Theory of the JTC

Joint transform correlation means that object images and reference image are input simultaneously at the input plane. The cross-correlation operation can be performed by processing its joint power spectrum.[4,5] A schematic diagram of the JTC is shown in Fig. 1.

In Fig. 1, $t(x,y)$ is the object image, $r(x,y)$ is the reference image, and $(a,0)$ and $(-a,0)$ are their position coordinates, respectively. Then, the total input function can be expressed as

$$g(x_1, y_1)=t(x_1-a, y_1)+r(x_1+a, y_1) \ . \qquad (1)$$

If collimated coherent light is used, we can get the joint transform spectrum at the back focal plane P_2 of the first Fourier-transform lens FTL1:

$$G(u, v)=F[g(x_1, y_1)] = T(u, v) \exp(-i2\pi ua)+R(u, v) \exp(i2\pi ua) \ , \qquad (2)$$

where $u=x_2/(\lambda f)$, $v=y_2/(\lambda f)$, f is the focal length of the FT lens, and (x_2, y_2) are coordinates in the plane P_2. $G(u, v)$ is recorded by an intensity-recording medium such as a CCD camera, a hologram, or an SLM. The joint power spectrum recorded can be expressed as

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Paper 11063 submitted by *Acta Optica Sinica*, received June 12, 1993; revised manuscript received Dec. 22, 1993; accepted for publication Dec. 27, 1993.

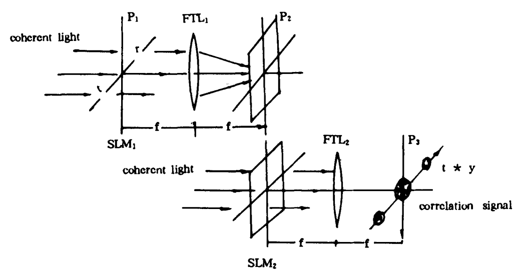


Fig. 1 Schematic diagram of joint transform correlator.

$$G(u, v)G^*(u, v) = T(u, v)T^*(u, v) + R(u, v)R^*(u, v) + T(u, v)R^*(u, v)\exp(-i4\pi ua) + R(u, v)T^*(u, v)\exp(i4\pi ua) , \quad (3)$$

which is the Fourier transform yielded by the second FT lens, FTL2. Then we can get the correlation result at the output plane P_3 (the back focal plane of FTL2):

$$I_c(x_3,y_3) = F[G(u, v)G^*(u, v)] = [t\star t] + [r\star r] + [t\star r]*\delta[x_3 - 2a, 0] + [r\star t]*\delta[x_3 + 2a, 0] , \quad (4)$$

where $\star$ and $*$ denote correlation and convolution, respectively. The first term of Eq. (4) is the autocorrelation of the object image; the second term is the autocorrelation of the reference image. The third and the fourth term, located at $(-2a, 0)$ and $(2a, 0)$, are cross-correlation terms, which are just the signals we want to detect. The cross-correlation term provides the information on the similarity between object image and reference image. Its location and orientation give information about the motion of the object.

3 Experimental Setup and Operating Process

Figure 2 shows the setup of our experimental system.[1,6,7] It is a single-arm, optically addressed, double-SLM structure. A digital system is used to input images automatically, post-process the output result, and refresh the reference image in real time through the object library, which includes different objects such as a variety of airplanes, tanks, etc.

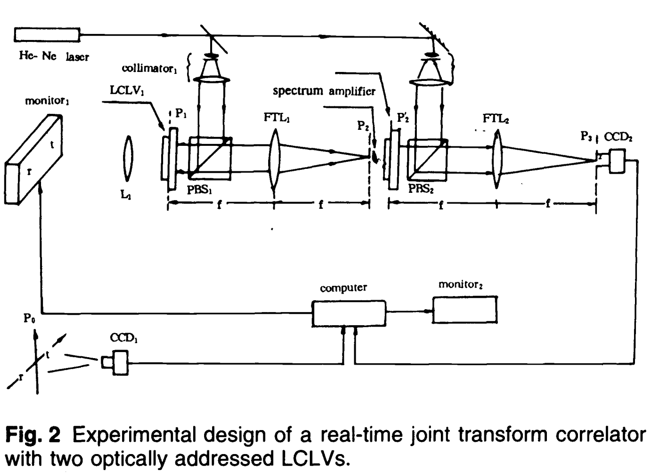


Fig. 2 Experimental design of a real-time joint transform correlator with two optically addressed LCLVs.

One of the key elements of the system is the LCLV. The LCLV was developed in the 1970s and has been extensively used as a spatial light modulator. Its operation is based on the electro-optic effect of liquid crystal layers. The LCLVs used in our experiment are model 90504, produced by the 28th Institute of Nanjin, China. Their operating parameters are as follows:

- maximum light aperture: 50 mm
- contrast: >100:1
- resolution: 17 pixels/mm (measured by resolution card)
- response time: rise time (0 to 90%) < 30 ms; fall time (100% to 10%)<100 ms
- reflectivity: >80% (for 633 nm)
- optical quality of surface: <2λ.

By using an image system, input images are imaged onto the first light valve, whose output is read out by coherent light. An appropriate lens is selected to produce the Fourier transform at its back focal plane, where another light valve having a resolution of approximately 20 pixels/mm is installed for intensity-recording the joint transform spectrum between objects and reference image. In our experiment the aperture of the LCLV is 50 mm, and the focal length of L1 is 500 mm; thus the spatial frequency of the interference fringe produced by the spatially separated input images at plane P_2 is about 200 lines/mm. So a spectrum amplifier with amplifying power greater than 10 is necessary to amplify the interference fringe for LCLV2. The output of the second light valve is Fourier transformed by the output optics and imaged onto a CCD camera. The correlator is supported by a digital system consisting of analog-to-digital and digital-to-analog converters, a built-in object library, and an interface to the system's minicomputer.[7,8] So the output of the joint transform correlation can be digitized for subsequent processing, such as subtracting the fixed-pattern background noise, signal-to-noise ratio, and standard deviation.

4 Experimental Results

We provide an experimental investigation of the effects of the joint transform correlator. An airplane model was used as the object. The experiments are performed in both the absence and the presence of input scene noise. The LCLVs are operated at different degrees of nonlinearity by adjusting their bias supply frequency, bias supply voltage, and writing light intensity. Figure 3 shows the input-output characteristic

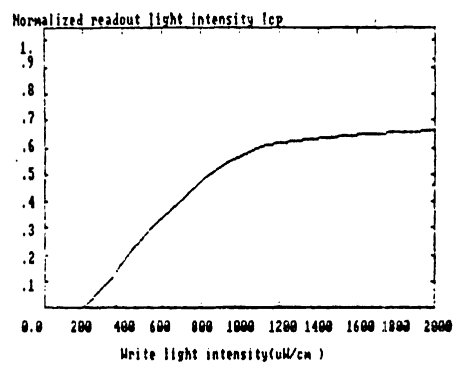


Fig. 3 The input-output characteristic curve of the LCLV used in our experiment.

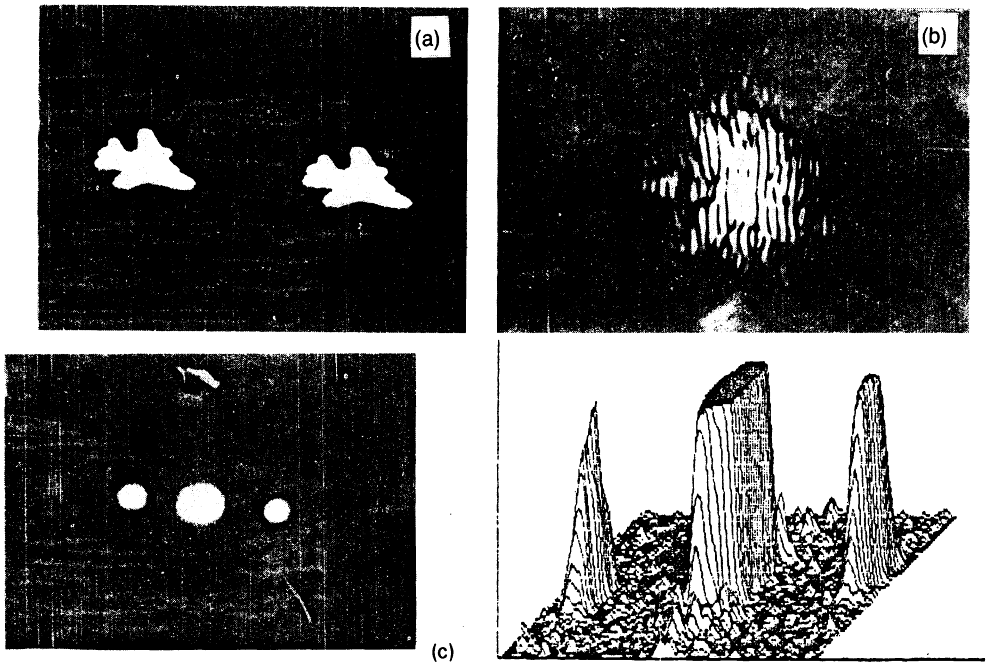


Fig. 4 The experimental results on the JTC with single input target: (a) input image as displayed on LCLV1, (b) joint transform power spectrum as displayed on LCLV2, and (c) correlation signal (photograph and 2-D plot).

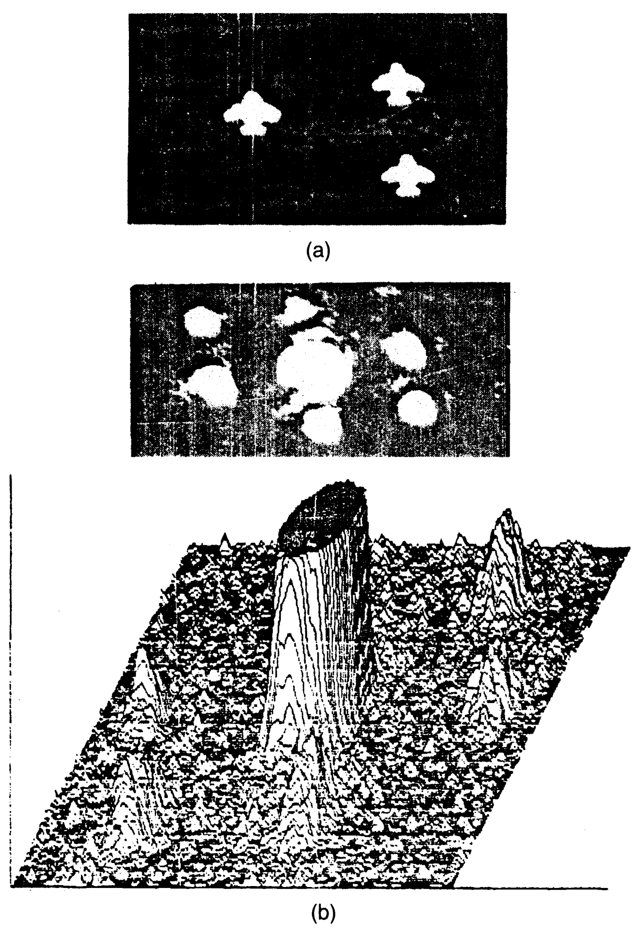


Fig. 5 The experimental results on the JTC with two input targets: (a) input image and (b) correlation signal (photograph and 2-D plot).

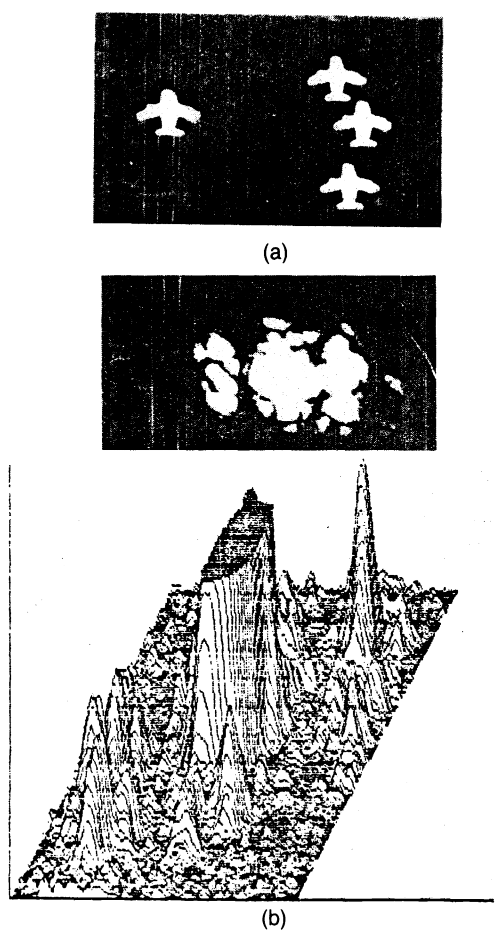


Fig. 6 The experimental results on the JTC with three input targets: (a) input image and (b) correlation signal (photograph and 2-D plot).

curve, indicating the nonlinearity of the device. The working parameters used in our experiments are size of images on LCLVs, 10 mm; write light intensity, 1600 μW/cm^2; readout light wavelength, 633 nm; readout light intensity, 250 μW/cm^2; focal length of FTLs, 500 mm; and effective aperture of optical devices, 40 mm. The bias supply voltage and frequency are 8V and 5 kHz for LCLV1, and 5V and 2kHz for LCLV2.

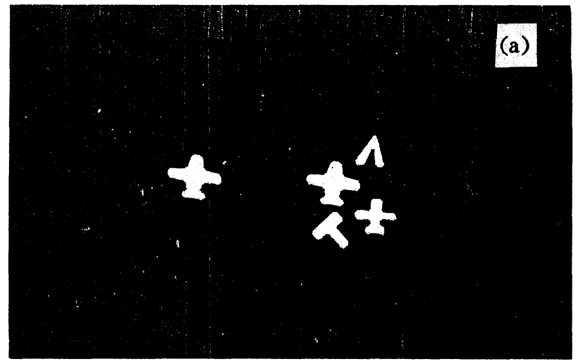
Figure 4 shows the experimental results for a single input object, where (a) is the input image displayed at LCLV1, (b) is the joint transform power spectrum displayed at LCLV2 (after amplification), and (c) is the correlation signal. Figure 5 shows the case of two input objects. Figure 6 shows the case of three input objects. Figure 7 shows the case of the object with noise. Figure 8 shows the fact that the intensity of correlation peak varies as the intensity ratio of object to reference image.

5 Discussion

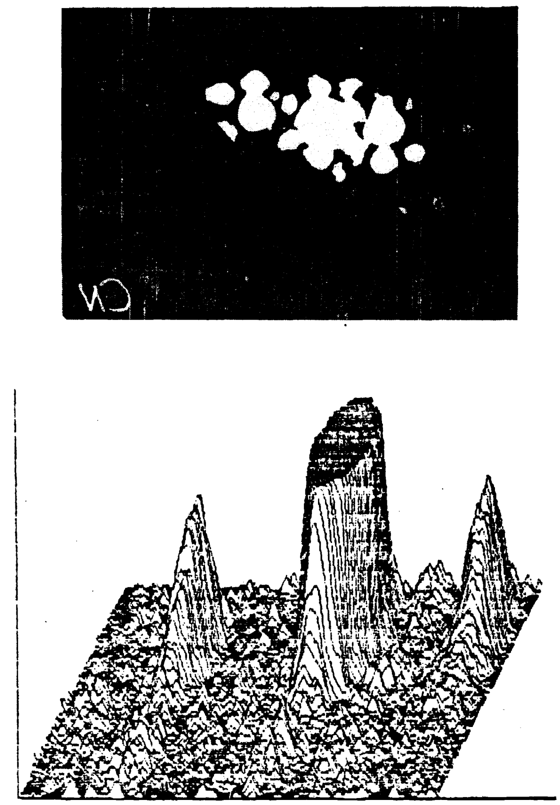
As shown in the preceding experiments, the JTC is a powerful technique for target recognition. It can give a high-quality correlation signal for a single-object input. In the case of multiple-object input, even if no more measurements are taken, the cross-correlation among the images will yield a useful signal. The more input objects, the more complex the intensity distribution over the output plane. In this case, besides the cross-correlation among object images, the cross-correlations between the reference image and all the object images will affect each other. Our analysis indicates that the distances between object images and reference image must satisfy some conditions in order to yield a good correlation signal. In addition, when the object images include noise, there is a disturbing signal in the zero-order region of the useful correlation signal. In particular, when object images undergo changes in orientation, scale, and intensity, the JTC cannot give good recognition. Further studies indicate that the output can be improved a great deal by using a composite reference image instead of the simple one.[8]

6 Summary

These initial results have demonstrated the object recognition capability of the JTC. Our next work is to improve the capability of the JTC for multiple-object recognition and classification and to realize invariant recognition. We are undertaking theoretical and experimental study of these problems. We believe that as elements such as SLMs and CCD detection devices are developed, real-time correlation will become a reality. As techniques are developed to solve various problems, more widespread applications will be implemented.



(a)



(b)

Fig. 7 The experimental results on the JTC, including noise: (a) input image with noise and (b) correlation signal (photograph and 2-D plot).

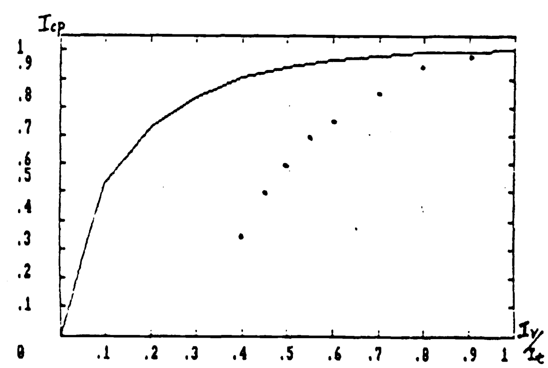


Fig. 8 The relationship between the correlation peak and the intensity ratio of object to reference image.

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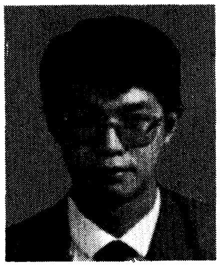

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