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The spatially-distributed recording of the composite filter using the pixelated liquid crystal display

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Abstract

A new recording method using a liquid crystal display (LCD) as an input device to synthesize a composite filter is presented. The filter in the optical correlator makes use of the multiple diffraction orders from the pixelated structure of the LCD panel. During the recording stage, each training pattern is sequentially recorded as a sub-filter at different diffracted order by holographic technology. After that, an input pattern could be simultaneously processed with all sub-filters in parallel such that the composite filter can be achieved. This recording method with spatial distribution could avoid the low efficiency of the conventional multi-exposure. The simulations and experimental results show that this system can perform invariant correlation as a composite filter. © 1999 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Optical correlator shows potential applications for real time pattern recognition, classification and tracking. However, it is very sensitive to even small changes relative to reference pattern. To improve the performance of a correlator for invariant recognition, several mathematical and technical methods have been studied [1]. In summary of these works, a final reference pattern denoted as synthetic discriminant function (SDF) is derived from the linear combination of the training pattern set and then synthesized as a composite filter. Various algorithms are used to determine the weighting coefficient of each training pattern [2]. To implement the SDF, there are two configurations: one is synthesized in the spatial domain, the other is synthesized in the Fourier domain. The Fourier domain composite filter has the requirement of the larger dynamic range [3]. However, the distributed recording method of the Fourier domain composite filter in our system can diminish the requirement. Furthermore, the used recording methods for the Fourier domain composite filter can be classified as single-exposure or multi-exposure. The multi-exposure method has an advantage that it does not need a large dynamic range of the input device as compared with the single-exposure method. But it suffers from the low efficiency or overexposure [4]. In general, a spatial light modulator for the input device are pixelated (e.g., liquid crystal display (LCD)). The diffraction orders of the pixelated structure are distributed at different locations in Fourier plane [5]. Typically, only the zero order is used for recording in the conventional architecture. In this paper, we present a novel method to record the SDF spatially-distributed in the Fourier plane and then combine the distributed response in the output plane. That is, each weighted training pattern is recorded on the different position in the Fourier plane. During the recording stage, a sub-filter for a

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training pattern is recorded at a diffracted order. After sequentially holographic recording of all training patterns, a two-dimensional array of sub-filters is constructed. During the recognition stage, those sub-filters are illuminated simultaneously by all the diffracted orders of the Fourier spectra of the input pattern. This multi-exposure method with spatially-distributed recording has an advantage of that which has no problem of low efficiency or overexposure like the conventional one. In addition, it is obtained simply through diffraction order from the grating structure of the LCD device. It does not require additional components such as the phase grating [6].

In Section 2, the operation principle of the correlator with composite filter is described. In Section 3, the simulation and experimental results of a correlator with four training patterns are presented. Section 4 presents the design considerations, and finally, conclusions are presented in Section 5.

2. Principle of operation

We first describe the optical transmission property of the LCD panel. Our LCD panel is disassembled from Epson's projection television VPJ-2000. It has a structure of two-dimensional array of apertures as shown in Fig. 1. The white aperture represents a liquid crystal pixel, and the dark parts represent the opaque area containing thin film transistors (TFT) and the interconnection circuits of the driver. There are some interference fringes on some pixel. If the aperture function of each pixel is $p(x,y)$ and all pixels are turned on, then the amplitude transmission function of the LCD is:

$$g(x,y) = p(x,y) * \sum_{m=1}^{m-M} \sum_{n=1}^{n-N} \delta(x - ma, y - nb), \quad (1)$$

where a is the period of the LCD pixels in the x-(horizontal) direction and b is the period of the pixels in the y-(vertical) direction, δ is the Delta function, m and n are integral indices, M and N are pixel numbers in the x and y directions, respectively. The notation $*$ represents the convolution operation. Eq. (1) shows that the pixelated structure of the LCD panel behaves like a two-dimensional grating.

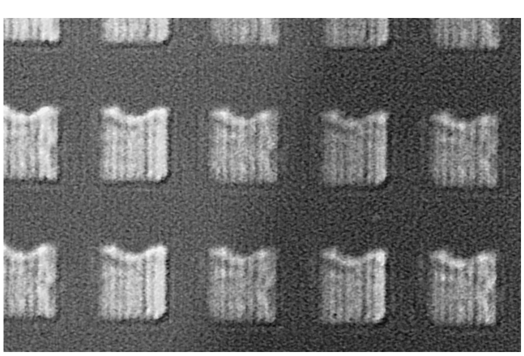

Fig. 1. The structure of two-dimensional array of apertures in the LCD.

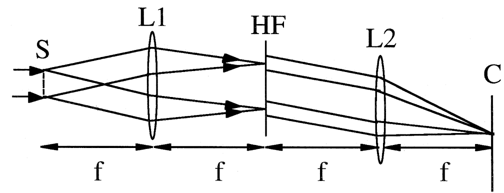

Fig. 2. The schematic diagram of the correlator with the composite filter.

When an input pattern is displayed on the LCD panel, each LC pixel is driven by an electrical signal which is proportional to the average brightness of the pattern at the corresponding area. If the function of input pattern varies slowly in comparison with the pixel function $p(x,y)$, then the averaging effect on the input pattern by LCD can be neglected. Thus, the amplitude transmission function of the LCD panel with an input pattern can be obtained by the panel transmission function multiplied by the pattern function, that is;

$$t(x,y) = g(x,y)u(x,y) \quad (2)$$

where $u(x,y)$ is amplitude function of input pattern. When the dimension of the input pattern is smaller than that of the LCD, i.e., neglecting the boundary effect of the LCD, thus, Eq. (2) can be expressed as:

$$t(x,y) = \left[p(x,y) * \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \delta(x - ma, y - nb) \right] \times u(x,y), \quad (3)$$

where the summation becomes a two-dimensional comb function. Its Fourier transform is still a comb function.

Now, we can consider the correlator with this LCD as an input device. Fig. 2 represents the schematic diagram of the correlator with the composite filter. An LCD is placed in the front focal plane (S) of a Fourier lens (L1) and the multiple diffraction orders of the Fourier transformation is obtained in the rear focal plane (HF) of the lens. In this figure, there are only two orders shown for illustration. Then, the distribution function in the Fourier plane can be written as:

$$T(f_x,f_y) = \sum_{m=-\mu}^{\mu} \sum_{n=-\nu}^{\nu} P\left(\frac{m}{n}, \frac{n}{b}\right) U\left(f_x - \frac{m}{a}, f_y - \frac{n}{b}\right), \quad (4)$$

where $P(f_x, f_y)$ is the Fourier transform of the pixel transmission function $p(x,y)$ and $U(f_x, f_y)$ is the Fourier transform of the input pattern $u(x,y)$. If the number of the diffraction orders is limited by the aperture of the lens, then m and n will have to be changed from infinite to finite number μ and ν. For simplicity, the aperture of lens is assumed to be rectangular and its dimension is much larger than that of the input pattern. The indices ranges of the diffraction order can be written as:

$$\mu = \frac{2a}{\lambda}\sin\left[\frac{1}{2}\tan^{-1}\left(\frac{A}{2f}\right)\right],$$

and

$$\nu = \frac{2b}{\lambda}\sin\left[\frac{1}{2}\tan^{-1}\left(\frac{B}{2f}\right)\right], \tag{5}$$

where λ is the wavelength, A and B are the aperture dimensions of the lens, and f is the focal length of lens. Eq. (4) shows that the function $T(f_x, f_y)$ is the summation of the spectrum duplicates of the input pattern $U(f_x, f_y)$ multiplied by the spectrum of the pixel transmission function $P(f_x, f_y)$ at each diffraction order (m,n). The factor $P(m/a,n/b)$ is related to the aperture ratio of LCD.

During the recording stage for synthesizing the composite filters, an aperture is sequentially placed at the position of the desired orders such that the whole Fourier plane is blocked except the desired sub-filter is opened and a training pattern is exposed. The aperture must have a dimension determined by the spectrum of the highest spatial frequency of the input pattern. Because the carrier consisted of pixel function which is not bandwidth limited, thus the input pattern has the possibility that its bandwidth is larger than the pixel frequency. For complete separation of each sub-filter, the input pattern must have a limitation that its bandwidth is smaller than one-half of the pixel frequency of the LCD. That is, the largest size of the aperture for this input condition is $(\lambda f/a, \lambda f/b)$. If the training pattern for the (m,n)th order is specified as $h_{m,n}(x,y)$ and the dummy variables (m,n) is changed to (m',n') in Eq. (4), then the Fourier spectra passing through the aperture will be expressed as:

$$S_{m,n}(f_x,f_y) = \sum_{m'=-\mu}^{\mu}\sum_{n'=-\nu}^{\nu} P\left(\frac{m'}{a},\frac{n'}{b}\right) \times H_{m',n'}\left(f_x-\frac{m'}{a}, f_y-\frac{n'}{b}\right)\mathrm{rect} \times\left[a\left(f_x-\frac{m}{a}\right), b\left(f_y-\frac{n}{b}\right)\right], \tag{6}$$

where $H_{m,n}$ is the Fourier transform of $h_{m,n}$. All other orders of the spectrum except the (m,n)th order will be blocked by the aperture. Therefore, the spectrum distribution from Eq. (6) becomes:

$$S_{m,n}(f_x,f_y) = P\left(\frac{m}{a},\frac{n}{b}\right)H_{m,n}\left(f_x-\frac{m}{a}, f_y-\frac{n}{b}\right). \tag{7}$$

For holographic recording, a plane wave is used as the reference beam for all sub-filters. In addition, all the training patterns are located at the same position. Therefore, the correlation outputs of all training pattern are summed up in the output plane. This condition is required for positioning and the tolerance with the input of the interval pattern. For simplicity, we consider the case that the correlation peaks from all the training patterns are assumed the same. For example, the training pattern is the rotational version of true class pattern. As indicated by Eq. (7), the Fourier spectrum of each order has different strength, which is proportional to $P(m/a,n/b)$. In order to compensate this difference for the DSF with the equal correlation peak, we adjusted the exposure time for each order such that the weighting coefficient are inversely proportional to $P(m/a,n/b)$ so that the correlation peak of the true class from each sub-filters are equal. Here, we made the assumption that the diffraction efficiency of the recording media is linearly proportional to the exposure time before saturation. In addition, the reference beam for the recording is also adjusted to be proportional to the intensity of each diffraction order. As a result, the complex conjugated term in the amplitude transmittance function of the composite filter can be written as:

$$S(f_x,f_y) = \sum_{m=-\mu}^{\mu}\sum_{n=-\nu}^{\nu}\frac{a_{m,n}P^*\left(\frac{m}{a},\frac{n}{b}\right)}{\left|P\left(\frac{m}{a},\frac{n}{b}\right)\right|^2} \times H'^*_{m,n}\left(f_x-\frac{m}{a}, f_y-\frac{n}{b}\right), \tag{8}$$

where the denominator is the intensity of each diffraction order and $a_{m,n}$ is the weighting coefficient determined by various algorithm. If the diffraction efficiency of the phase hologram is proportional to the modulation index, e.g., thermal plastic plate [7], then:

$$H'_{m,n}(f_x,f_y) = \left[\frac{I_0^{\frac{1}{2}}\left|H_{m,n}(f_x,f_y)\right|}{I_0+\left|H_{m,n}(f_x,f_y)\right|^2}\right]^{\frac{1}{2}} \times\frac{H_{m,n}(f_x,f_y)}{\left|H_{m,n}(f_x,f_y)\right|} \tag{9}$$

where I_0 is the intensity of the reference beam. Thus, the composite filter consists of the frequency-weighted training patterns.

After recording, the system can be used to perform optical correlation. Now the aperture in the Fourier plane is removed so that all the sub-filters can be simultaneously illuminated by the diffraction orders of the input pattern. The correlation output is expressed as:

$$R(x',y') = \mathrm{FT}\{T(f_x,f_y)S(f_x,f_y)\}, \tag{10}$$

where FT{} is the Fourier transform operation and $T(f_x, f_y)$ is the input spectrum. By substituting Eq. (4) and Eq. (8) into Eq. (10), we obtain:

$$R(x',y') = \mathrm{FT}\left\{ \sum_{m=-\mu}^{\mu} \sum_{n=-\nu}^{\nu} a_{m,n} U\left(f_x - \frac{m}{a}, f_y - \frac{n}{b} \right) \times H'^{*}_{m,n}\left(f_x - \frac{m}{a}, f_y - \frac{n}{b} \right) \right\}. \quad (11)$$

In obtaining the above result, we have also used the condition that the input pattern has a bandwidth smaller than one-half of pixel frequency of the LCD. Hence, each diffraction order does not readout the adjacent sub-filters. That is, when $m \neq m'$ or $n \neq n'$, we have:

$$U\left(f_x - \frac{m}{a}, f_y - \frac{n}{b} \right) H'^{*}_{m',n'}\left(f_x - \frac{m'}{a}, f_y - \frac{n'}{b} \right) = 0,$$

which leads to Eq. (11). The condition of bandwidth will avoid the cross-talk between adjacent sub-filters.

Rearranging Eq. (11), the output distribution becomes:

$$R(x',y') = \sum_{m=-\mu}^{\mu} \sum_{n=-\nu}^{\nu} a_{m,n} \exp\left[j2\pi\left(\frac{m}{a}x' + \frac{n}{b}y' \right) \right] \times u(x',y') \otimes h'^{*}_{m,n}(x',y')$$

$$R(x',y') = \sum_{m=-\mu}^{\mu} \sum_{n=-\nu}^{\nu} a_{m,n} \exp\left[j2\pi\left(\frac{m}{a}x' + \frac{n}{b}y' \right) \right] \times R_{m,n}(x',y'), \quad (12)$$

where $\otimes$ denotes the correlation operation and $h'_{m,n}$ is Fourier transform of $H'_{m,n}$. Thus, the final output can be interpreted as the summation of the weighted correlations multiplied by the phase terms from all sub-filters. The correlation from each sub-filters is the correlation operation of the input pattern $u(x,y)$ with each frequency-weighted training pattern $h'_{m,n}$. For pattern classification by threshold detection, Eq. (12) must satisfy the constrain:

$$\max\{|R(x',y')|\} > \max\{|R'(x',y')|\}, \quad (13)$$

where R is the output signal when the input is true class pattern. R' is the output signal when the input is false class pattern.

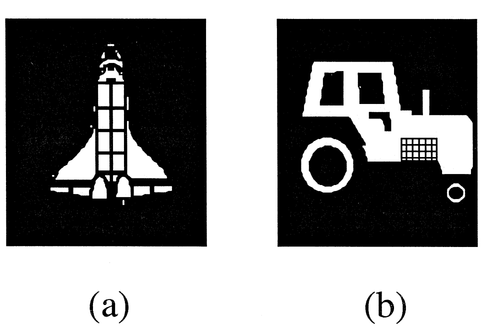

Fig. 3. The input patterns used for the simulation. (a) A space shuttle is specified as the true class. (b) A car is specified as the false class.

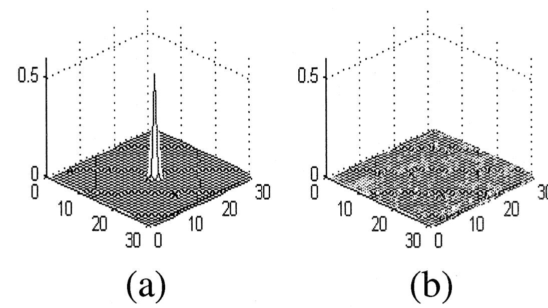

Fig. 4. The correlation outputs. (a) The true class correlation output. (b) The false class correlation output.

3. Numerical and experimental demonstration

In order to investigate the feasibility of a correlator with distributed composite filter, a computer simulation of four sub-filters correlator was performed. The input patterns used for the simulation were shown in Fig. 3. Fig. 3a shows a space shuttle which is specified as the true class and Fig. 3b, a car, is specified as the false class. The four training patterns are the space shuttles at the orientation of 0, 90, 180 and 270°. For preserving the equal exposure and

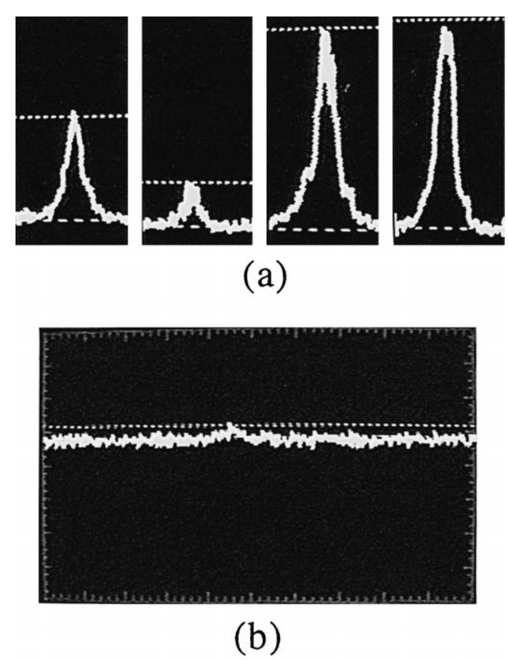

Fig. 5. The experimental results. (a) The line scans of the correlation profiles when the input is one of the four training patterns; (b) when the input is a car.

the reference beam, the training patterns were recorded in the diffraction orders of (1,2), (−1,2), (−1,−2), and (1,−2), respectively. The dimension of input and Fourier plane is 279 × 279 which had the effect like a rect function of the aperture in Eq. (5). That is, the dimension has been selected to satisfy the condition of the input pattern as mentioned in above analysis. Because the contribution of the random noise to the correlation peak is small, the weighting coefficients $a_{m,n}$ are assumed to be the same. Fig. 4a shows a peak in the central part of the correlation output when the input is one of the training patterns. Fig. 4b shows no peak in the central part of the correlation output when the input is the false class. When the inputs are the other training patterns, the correlations also have the same peak values. Furthermore, we demonstrated the results with the experiments. The thermal plastic plate was used as the recording media. When the input is one of the 4 training patterns, the line scans of the correlation profiles have peaks as shown in Fig. 5a. The differences between peaks are due to non-uniform of the spatial response of the recording media. When the input is a car, there is no peak as shown in Fig. 5b. Comparing the two figures, this correlator evidently satisfies the constrain as described in Eq. (13). In addition, the large discrimination ability from the results presents the potential of recording more sub-filters.

4. Discussions

There are some considerations for the design with more sub-filters. From the constraint described in Eq. (13), the left hand side is the summation of one correlation peak from one of the sub-filters and random noises from the other sub-filters. The right hand side is the summation of random noises from all the sub-filters. Thus, it is evident that increasing the discrimination ability of each sub-filter will increase the probability of satisfying the constrain. One convenient method for adjusting the discrimination ability is that the sub-filters are recorded for the characteristic frequencies of the spectrum. This can be achieved by adjusting the intensity of the reference beam to that of higher spatial frequencies of the pattern as described in Eq. (9). However, because of its low tolerance to the true class input which is not included in the training set, the required number of the training set will be increased.

The saturation of diffraction–exposure relation of the recording media will decrease the correlation peak when the weaker diffraction orders normalize as described by Eq. (8). On the other hand, the system noise will increase the minimum value of the normalization. These two limitations denoted as the dynamic range of the system will limit the available number of the sub-filters. That is, applying the larger number of sub-filters will require larger dynamic range. If the available dynamic range is dominantly determined by the diffraction efficiency and the scattering noise

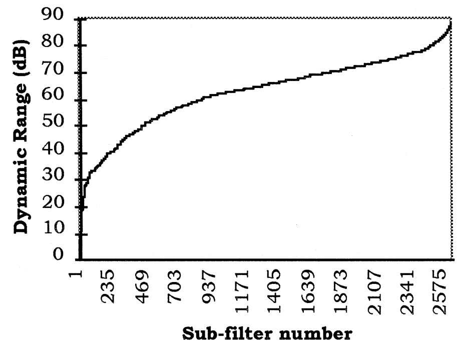

Fig. 6. The relationship between dynamic range requirement and the number of available sub-filters for the LCD.

of the hologram media, the available sub-filter number can be estimated from the property of the recording media. For example, the relationship between dynamic range requirement and the number of available sub-filters for the LCD in VPJ-2000 is shown in the Fig. 6. If we use a silver halide plate as filter recording media, which has dynamic range of diffraction efficiency about 90 dB, then the available number of the sub-filters is 2575. Because each pixel of the LCD is not identical, the pixel function $p(x,y)$ in Eq. (1) cannot be determined from any one. Thus, this relationship is estimated by measuring the intensity of each orders on the axes and then calculate the other orders.

In the case of the large number of the sub-filter, the discrimination ability of the composite filter will become small. Therefore, the dynamic range of LCD for correlation detection will determine the number of the sub-filter. The available sub-filter number is also limited by the aperture of Fourier lens. This is the vignetting effect of Fourier transform by lens. By considering all these factors together mentioned above, the total number of available sub-filter can be estimated.

5. Conclusions

In this work, we have described the operation principle of a correlator with composite filter using an LCD plate as the input device and demonstrated a system with four training patterns, in which, four patterns with different orientations were also used as the input patterns. The sub-filters were located at four diffraction orders of the Fourier spectra. It has shown that this system possesses the capability of the pattern classification. The LCD is the most popular input device, however, the drawback using LCD is that the amplitude of each diffracted order strongly depends on the structure of LCD pixels and the profile of each pixel is not identical. The theoretical description of the intensity of each order is not available. In order to obtain the desired contribution from all sub-filters, we must measure the intensity of each order and design an exposure schedule to record the training set.

In summary, the simulation and experimental results show that the composite filter implemented by the pixelated LCD and spatially-distributed recording method has potential of utilizing the large number of training sets.

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References

[1] B.V.K. Vijaya Kumar, Appl. Opt. 31 (1992) 4773.
[2] S. Yin, M. Lu, C. Chen, F.T.S. Yu, T.D. Hudson, D.K. McMillen, Opt. Lett. 20 (1995) 1409.
[3] F.T.S. Yu, M. Lu, G. Lu, S. Yin, T.D. Hudson, D.K. McMillen, Opt. Eng. 34 (1995) 3200.
[4] J.T. LaMacchia, C.J. Vincelette, Appl. Opt. 7 (1968) 1857.
[5] A. Vargas, J. Campos, M.J. Yzuel, C. Iemmi, S. Ledesma, Appl. Opt. 37 (1998) 2063.
[6] F.T.S. Yu, Q.H. Zhou, Opt. Commun. 64 (1987) 111.
[7] K. Ohnuma, T. Honda, J. Tsujiuchi, Opt. Commun. 36 (1981) 1.