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DISTORTION-INVARIANT OPTICAL PATTERN RECOGNITION  
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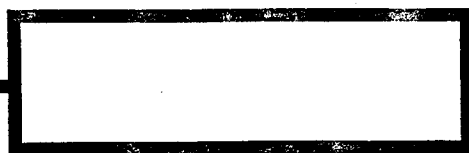
Yang Baotang, Lan Zhengping



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DISTORTION-INVARIANT OPTICAL PATTERN RECOGNITION BY  
CORRELATIVE MATRIX FEATURE CRITERION

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**Abstract**

In this paper, we used correlative matrix as a feature criterion in K-L transformation for feature compression, and then the synthetic matched filter (SMF) was prepared by means of the synthetic discriminant function (SDF). This method can effectively reduce the size of feature image. By this filter, the shift, scale and rotation invariant optical pattern recognition was realized with a high signal noise ratio of correlation output.

**Key words:** information processing, optical pattern recognition, matched filter, computer-generated hologram, K-L transformation.

I. Introduction

Since Vander Lugt [1] proposed using the holographic recording method in fabricating the well-known complex-number matched-spatial-filter great progress has been obtained in coherent optical pattern recognition. However, the complex-number matched-spatial-filter is incapable of solving the problem of multi-aspect invariant pattern recognition. Later on, Casasent et al proposed using the synthetic discriminant function (SDF) to fabricate a matched filter [2]; thus, the invariant deformation problem is solved more satisfactorily. However,

there are still some imperfections to be solved [3]. One of them is the reduction of the signal-to-noise ratio with increase in the number of training tests [4]. In this paper, the correlative matrix is used as the feature criterion and the number of characteristic patterns for compression in the K-L transform [5]. Then the SDF method is employed to synthesize the pulse response function of the matched filter. By using the method of computer-generated holograms [5], a synthetic matched filter is fabricated. In the coherent optical pattern processing system, three-aspect (translation, rotation, and scaling) invariant optical pattern recognition is accomplished.

## II. Filter Algorithms

### 1. The SDF method

Various deformations of the target pattern are composed into a function sequence  $\{f_n\} (n=1, 2, \dots, N)$ . Let us assume that the pulse response  $h(x, y)$  of the matched filter is the linear set  $\{f_n\}$

$$h(x, y) = \sum_{m=1}^N a_m f_m \quad (1)$$

if the inputted pattern is a certain deformation  $f_n$  of the target pattern, it is required that the output of the correlation of  $h(x, y)$  at the origin of coordinates is a constant, for example,

$$g(0, 0) = \iint_{-\infty}^{+\infty} f_n(x, y) h(x, y) dx dy = 1. \quad (2)$$

By substituting Eq. (1) into Eq. (2), we obtain

$$\sum_{m=1}^N a_m r_{nm} = 1, \quad r_{nm} = \iint_{-\infty}^{+\infty} f_n(x, y) f_m(x, y) dx dy, \quad (3)$$

Define  $\{f_n\}$  as a correlative matrix

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1N} \\ r_{21} & r_{22} & \dots & r_{2N} \\ \vdots & \vdots & & \vdots \\ r_{N1} & r_{N2} & \dots & r_{NN} \end{bmatrix}, \quad (4)$$

By using the vector symbol for the matrix. Eq. (3) can be written as follows:

$$R\alpha = U, \quad (5)$$

In the equation  $U$  is a row vector for the matrix element at (1); row vector  $\alpha$  is determined by the following equation

$$\alpha = R^{-1}U. \quad (6)$$

From the equation, the function  $h(x,y)$  can be determined as satisfying Eq. (2), thus obtaining a matched filter with the deformation-invariant feature.

## 2. K-L Transform

Briefly speaking, by using a characteristic vector corresponding to the characteristic value of the matrix, thus constituting an orthogonal transform (of the transform matrix), which is called the K-L transform [5]. If for a certain  $M$ -dimensional vector all characteristic values of the covariant matrix are arranged according to a decreasing sequence  $(\lambda_1 > \lambda_2 > \dots > \lambda_n)$ , the transform matrix constituted by the characteristic vector corresponding to the first  $K$  ( $1 < K < M$ ) characteristic values, to this  $M$ -dimensional vector the K-L transform is connected. Then the  $M$ -dimensional vector is compressed into a  $K$ -dimensional vector. From the geometric significance, it can be considered as a new  $M$ -dimensional space transformed from a vector of  $M$ -dimensional space. In the new space, the projections onto  $M-K$  ( $1 < K < M$ ) axes is zero or very small, therefore it can be neglected. Thus, a  $M$ -dimensional problem is transformed into a  $K$ -dimensional problem.

## 3. Algorithm of synthetic matched filter

To apply the K-L transform to a pattern processing problem, the first problem to be solved is how to select the initial vector before conducting the K-L transform, thus compressing the number of dimensions. The method used is as follows:

assume that there exist  $M$  training sample patterns; in each pattern there are  $N=L \times L$  sampling points, then we can have a vector sequence  $\{A(j)\}, (j=1, 2, \dots, M)$ . There are  $n$  dimensions in each vector. From this  $M$   $N$ -dimensional vector we can constitute

a matrix A

$$A = \begin{bmatrix} a_1^{(1)} & a_1^{(2)} & \dots & a_1^{(M)} \\ a_2^{(1)} & a_2^{(2)} & \dots & a_2^{(M)} \\ \vdots & \vdots & & \vdots \\ a_n^{(1)} & a_n^{(2)} & \dots & a_n^{(M)} \end{bmatrix} = [A^{(1)} A^{(2)} \dots A^{(M)}], \quad (7)$$

There are nxm orders for this matrix. Let  $B=A^T$ , and we obtain

$$B = \begin{bmatrix} a_1^{(1)} & a_1^{(2)} & \dots & a_n^{(1)} \\ a_2^{(1)} & a_2^{(2)} & \dots & a_n^{(2)} \\ \vdots & \vdots & & \vdots \\ a_1^{(M)} & a_2^{(M)} & \dots & a_n^{(M)} \end{bmatrix} = [B_1, B_2, \dots, B_M], \quad (8)$$

Here,  $B_i^T = (a_i^{(1)}, \dots, a_i^{(M)})$ , ( $i=1, 2, \dots, n$ ) is of the M-dimensional vector. This N vector  $B_i$  is selected as the initial vector.

From the exterior product of  $(B_i - \bar{B}_i)$ , we obtain a matrix C

$$\left. \begin{aligned} C_i &= (B_i - \bar{B}_i)(B_i - \bar{B}_i)^T, \quad (i=1, 2, \dots, n) \\ \bar{B}_i &= \sum_{j=1}^M \rho_j a_i^{(j)} \end{aligned} \right\} \quad (9)$$

Here  $\bar{B}_i$  is the probability mean of vector  $B_i$ . Assume in M training samples that the emerging probability is the same; by selecting  $\rho_j = (1/M)$ . The matrix C is of MxM order. By solving the intrinsic value  $\lambda$  and the intrinsic vector W of this matrix, and arranging the intrinsic values in a decreasing sequence, we obtain  $\lambda_1^{(1)} \lambda_1^{(2)} \dots \lambda_1^{(M)}$  and  $\{W_i^{(j)}\}$ , ( $j=1, 2, \dots, M; i=1, 2, \dots, n$ ). Here, with the exception of  $\lambda_1^{(1)} \neq 0$ ,  $\lambda_1^{(2)}, \dots, \lambda_1^{(M)}$  are all zero. Thus, it makes the method ineffective in compressing the number of characteristic patterns according to the magnitude of characteristic values. As the characteristic vector corresponding to zero characteristic values is not unique, a new criterion should be sought after.

Let us use the correlative matrix as the new criterion. Thus, first we derive from Eq. (9) the intrinsic value W for the transform.

$$B'_i = [W_i^{(1)} W_i^{(2)} \dots W_i^{(M)}]^T B_i = \begin{bmatrix} a_i^{(1)} \\ a_i^{(2)} \\ \vdots \\ a_i^{(M)} \end{bmatrix}, \quad (10)$$

In the equation  $a_i^{(j)} = W_i^{(j)} B_i$ , ( $j=1, 2, \dots, M; i=1, 2, \dots, n$ ), thus we obtain a matrix  $B'$

$$B' = \begin{bmatrix} a_1^{(1)} & a_2^{(1)} & \dots & a_n^{(1)} \\ a_1^{(2)} & a_2^{(2)} & \dots & a_n^{(2)} \\ \vdots & \vdots & & \vdots \\ a_1^{(M)} & a_2^{(M)} & \dots & a_n^{(M)} \end{bmatrix}, \quad (11)$$

With transposition of  $B'$  and letting  $B'^T = A'$ , we obtain

$$A' = \begin{bmatrix} a_1^{(1)} & a_1^{(2)} & \dots & a_1^{(M)} \\ a_2^{(1)} & a_2^{(2)} & \dots & a_2^{(M)} \\ \vdots & \vdots & & \vdots \\ a_n^{(1)} & a_n^{(2)} & \dots & a_n^{(M)} \end{bmatrix} = [A'^{(1)} A'^{(2)} \dots A'^{(M)}]. \quad (12)$$

Each row vector of  $A'$  is considered as a new characteristic pattern; there is a total of  $M$  patterns. Next, solve for the correlative matrix

$$R = A'^T A' = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1M} \\ r_{21} & r_{22} & \dots & r_{2M} \\ \vdots & \vdots & & \vdots \\ r_{M1} & r_{M2} & \dots & r_{MM} \end{bmatrix}. \quad (13)$$

The self-correlated  $\Lambda_{jj}$  is arranged in a decreasing sequence; taking the first  $K$  ( $1 < K < M$ ), use the  $K$  vectors (corresponding to  $K$  values)  $A'^{(j)}$  ( $j=1, 2, \dots, K$ ) as a new characteristic pattern. To this new  $K$  characteristic pattern, a synthesis is conducted by using the SDF mentioned previously; we can obtain a pulse response function of the synthetic matched filter with high signal-to-noise ratio with the deformation-invariant feature.

Since the characteristic vector corresponding to the zero value is not unique, possibly all values on the main diagonal of the correlative matrix are greater than the threshold value, thus incapable of effectively accomplishing the characteristic compression. At this stage, a special solution should be re-established, then solving for the homogeneous equation set in order to conduct characteristic compression by again using the characteristic criterion method of the correlative vector until we obtain a satisfactory characteristic compression.



### III. Experimental Results and Discussion

To accomplish the three-aspect (translation, rotation, scaling) invariant optical pattern recognition by using the synthetic matched filter, first calculate the filter by using the algorithm described in this paper. Thus, by selecting letter "E" as the target pattern, with three different scale ratios (0.5:1:1.5) and five orientations (within the range between zero degrees and 60 degrees, with a 15-degree spacing), totalling 15 patterns as the initial sample for the K-L transform, characteristic compression is conducted by using the characteristic criterion method of the correlative matrix. As revealed in the calculation results, in this problem the 15 characteristic patterns can be compressed into three characteristic patterns. Then there are three characteristic patterns as used a new function sequence; by using the SDF method, synthesize the matched filter.

Before conducting the optical correlative pattern recognition experiment, first a computer was used in simulation. The letter "E" was used as the input pattern (refer to Fig. 1 (a)) with scale ratio of 1, orientation angle of  $0^{\circ}$ , as well as 1.4 as the scale ratio and  $30^{\circ}$  as the orientation angle, the synthetic matched filter from the computation was used as the spatial filter; the corresponding three-dimensional diagram of input power spectrum is shown in Fig. 1(b). For convenient comparison, the SDF method is also used to synthesize the 15 initial samples, thus obtaining the SDF of another spatial filter; the three-dimensional diagram of the correlative output power spectrum is shown in Fig. 1(c). From Fig. 1, we can see for the SDF of the 15 initial samples, the top terminals of the correlative output are comparatively flat; thus, it is difficult to determine the position of maximum value as the background noise is very high. By using only the synthetic matched filter of three characteristic patterns, the correlative output has a

clear sharp peak; the background is relatively low. According to the following equation, calculate the signal-to-noise ratio:

$$SNR = \frac{g^2(0, 0)}{\frac{\iint_S g(x, y) dx dy}{\iint_S dx dy}}, \quad (14)$$

In the equation,  $g(x, y)$  is the correlative value at point  $(x, y)$  of the output plane;  $S$  is the area of the entire output plane. Refer to Table 1 for the computational results. In the table, No. 1, No. 2, and No. 3 indicate the input diagram with scale ratios of 0.5, 1, and 1.5, respectively. We can see that within the synthetic range of the synthetic filter, the signal-to-noise ratio of the synthetic matched filter (SMF) is higher by about 20 to 23 percent of the SDF.

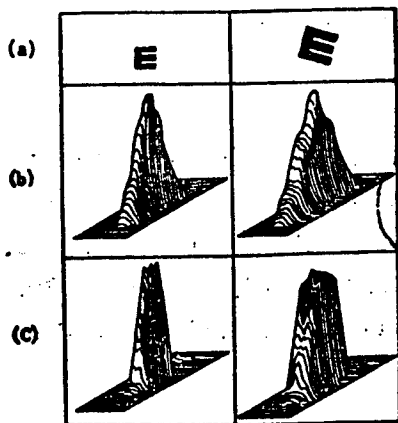


Fig. 1 Computer simulation of the optical correlative calculation. (a) Input samples, (b) Output results with SMF, (c) Output results with SDF.

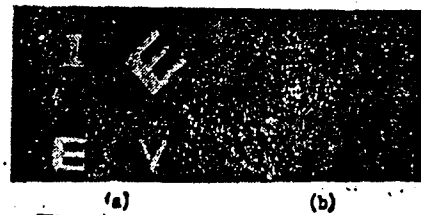


Fig. 2 Experiment of optical correlation: (a) input, (b) output.

Finally, by using the method of computer-generated holograms, the calculated SMF is made into a Fourier-transform hologram [6] of two elements Lohmann III type, to be used as the spatial filter in the coherent optical pattern processing system. The input diagram shown in Fig. 2(a) is placed in the input plane, then the output results obtained on the output plane are shown as in Fig. 2(b). From Fig. 2 we can see that in the optical correlative pattern recognition experiment, if target "E" appeared in the input plane, whatever the occurrence of translation, rotation, or scaling variation, only the scale ratio and orientation angle fall within the synthetic range of the SMF, then a clear correlative bright spot appears at the corresponding position of the output plane. However, for other letters in the input plane, there are no clear bright spots in the output plane. This indicates that the three-aspect (translation, rotation, and scaling) invariant optical pattern recognition can be realized by using an SMF.

(1) In the K-L transform, the correlative matrix is used as the characteristic criterion, thus enabling effective compression to be carried out on the number of characteristic patterns.

(2) The characteristic patterns obtained after characteristic compression are used as a new function sequence; the fabricated SMF can have a higher signal-to-noise ratio than such filters fabricated by using the SDF method.

(3) The computer simulation and optical experimental results prove that the above-mentioned SMF has a three-aspect (translation, rotation, scaling) invariance in the correlative

output within the range of the synthetic scale and orientation angle.

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