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Colour Image Recognition

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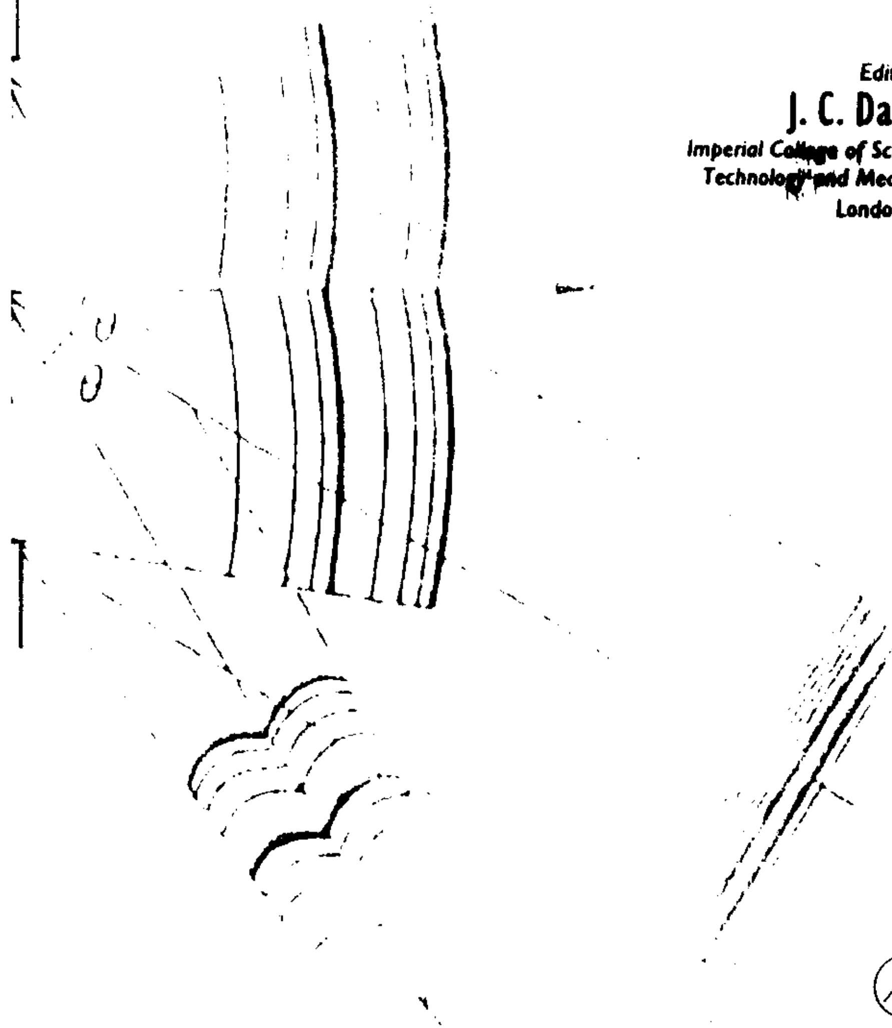

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CHAPTER FIFTEEN

Colour Information in Optical Pattern Recognition

M.J. Yzuel and J. Campos

15.1. INTRODUCTION

When we speak about pattern recognition, people may think that we intend to obtain with a machine what a human being usually does. But, what is the process of acquisition of information by the eye? Many authors (e.g. [1]) agree that the word "acquisition" covers not only a visual process but rather a series of processes (although different authors use different words): detection, which is understood as the awareness of the existence of local differences of energy; recognition, the awareness that an object is of a given class (e.g. a house or a car); identification, the ability to distinguish an object among other objects of its own class (e.g. a particular model in the case of a car).

In general the automatic process of pattern recognition is not based exactly upon the steps of the visual process, although it tries to recognize an object from other objects in the scene, which is the same problem that the human being solves. But is a machine capable of doing what the human brain does?

The equivalent to detection can be the selection (segmentation) of a zone in the scene because there is some object of interest. Recognition and identification by automatic methods are achieved by evaluating the similarity between the objects which appear in the scene with the objects of reference we have stored. This similarity may be evaluated by different methods and we will deal in this chapter with methods based on correlation, which can be implemented optically. Usually, by optical pattern recognition is understood either recognition or identification. Its goal is to detect the presence of a given object and to determine automatically its position in the input scene.

Optical image processing is carried out in general with monochromatic light. So it does not consider the colour information of the objects (variation of hue inside the object). Nevertheless colour information is considered in the literature for different purposes. One of them is when the colour is utilized to enhance the information of the image for an easier interpretation of it by the human eye. For instance, black and white images can be pseudocoloured according to the grey level or spatial frequency content [2]. The purpose of introducing colour in optical pattern recognition is twofold: improvement of the recognition process and an increase in processing capacity. The capacity may be increased because different wavelengths of light do not interfere with each other and they can process different information. As an example of this, Case [3] uses wavelength-multiplexed matched spatial filters in an incoherent optical pattern recognition system. Colour-coded correlation responses are produced to recognize several objects simultaneously.

The improvement of the recognition process when colour information is added is based on the fact that for a colour object both shape and intensity distribution may depend strongly on the illuminating wavelength. Then, colour may introduce more information for recognition.

Colour information is introduced in an optical correlator either through an image of the scene on a colour slide or by using spatial light modulators (SLM). In the first case if we illuminate the correlator with a white light source the transmissions for all wavelengths are available. Nevertheless in an optical correlator one works only with a finite number of wavelengths and the final information has to be obtained from the correlation in these channels. In the case of the SLM only a reduced number of channels are available (i.e. red, green and blue (RGB) from a colour CCD camera or any other channels obtained by a detector).

In this chapter we will present some possibilities to introduce colour information in image recognition by correlation methods. In Section 15.2, we will describe several architectures for colour pattern recognition proposed with white light source. In Section 15.3 some general problems that may appear in colour image recognition are stated and the corresponding strategies to solve them are described. In Section 15.4, we explain changes of chromaticity coordinates to utilize more efficiently the information provided by the available channels. Finally we make some general comments about the research in this field and some speculations about future possibilities.

15.2. WHITE-LIGHT IMAGE CORRELATION

Several architectures of an achromatic partially coherent processor with white light source have been proposed by Yu and other authors (e.g. [4] and [5] and the references contained in these review works).

This processor may be used as a correlator for optical pattern recognition of colour objects (Figure 15.1). An object transparency $o(x,y)$ is placed as an input image in contact with a sinusoidal grating, whose amplitude transmittance is given by $t(x,y) = 1 + \cos(p_0 x)$, where p_0 is the angular spatial frequency of the grating. If the source is a polychromatic point coherent source, the complex wave field in the Fourier plane for a wavelength λ is

$$O(\alpha,\beta;\lambda) = O(\alpha,\beta) + \frac{1}{2}\left[O\left(\alpha + \frac{f\lambda}{2\pi}p_0,\beta\right) + O\left(\alpha - \frac{f\lambda}{2\pi}p_0,\beta\right)\right] \qquad (15.1)$$

where $O(\alpha,\beta)$ is the Fourier transform of $o(x,y)$, and f is the focal length of the transform lens.

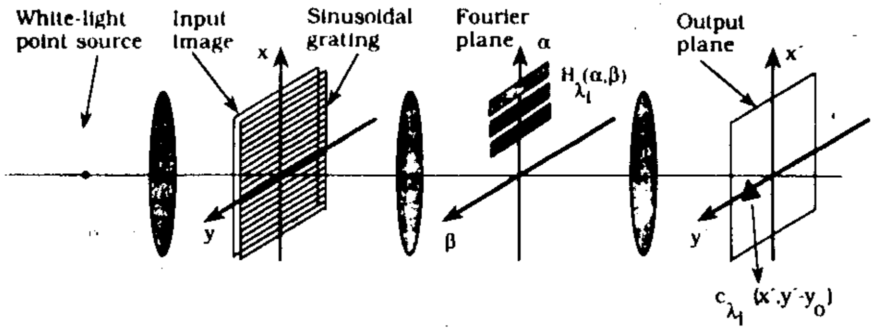

Figure 15.1 *White light image correlator.*

The object transparency may also be different for each wavelength. Let $o_{\lambda_i}(x,y)$ be the object function for λ_i. If the source contains three wavelengths (red, green and blue) the three spectra appear separated in the Fourier plane, centred at

$$\alpha = \pm\frac{f\lambda_i}{2\pi}p_0, \quad \beta = 0$$

Usually the signal is spatial frequency band limited and it is possible to calculate the frequency p_0 to separate the colour spectra.

The generation of the set of filters is as follows: if a colour target $g(x,y)$ has to be recognized, a set of matched filters are obtained sequentially with three coherent beams (red from a He–Ne laser and blue and green from an argon ion laser). A grating is used in contact with the target and a mask with different apertures is placed in the Fourier plane. When the red coherent source is on, the corresponding aperture is open for recording the spectrum of the target transmission for red, and the same for the other wavelengths.

The amplitude transmittance of the filter for λ_i is

$$H_{\lambda_i}(\alpha,\beta) = C_1 + C_2\left|G_{\lambda_i}\left(\alpha - \frac{f\lambda_i}{2\pi}p_0,\beta\right)\right|\cos\left[\frac{2\pi}{f\lambda_i}\beta y_0 + \phi_{\lambda_i}\left(\alpha - \frac{f\lambda_i}{2\pi}p_0,\beta\right)\right] \qquad (15.2)$$

where y_0 is related to the inclination of the reference wave used for the filter construction. C_1 and C_2 are proportionality constants and

$$G_{\lambda_i}(\alpha,\beta) = |G_{\lambda_i}(\alpha,\beta)|\exp i\phi_{\lambda_i}(\alpha,\beta) \qquad (15.3)$$

is the Fourier transform of the target transmittance for λ_i.

If this set of filters is introduced in the Fourier plane (Figure 15.1) the complex amplitude at the output plane contains, for each wavelength a term centred at $(0,y_0)$ which is the correlation of the scene input and the target: $c_{\lambda_i}(x', y' - y_0) = o_{\lambda_i}(x',y')*g_{\lambda_i}(x',y')$. The correlations for the different wavelengths are superposed at this point.

Two sets of spectral–spatial matched filters can be used if the conjugate pair of the colour Fourier spectra is utilized. With a rotating grating technique N colour signal recognitions can be performed.

Instead of a polychromatic coherent point source, a white-light source can be used [5]. With this architecture the annoying coherent artifact noise can be suppressed. If an extended white-light source is used, it is encoded to alleviate the stringent coherent requirement and the available light power from the source can be more efficiently utilized. A real-time polychromatic optical matched filtering technique has also been proposed [6] utilizing a spatial light modulator.

In another proposal ([5], p. 209) Yu describes a technique for generating a broad spectral band Fourier hologram with a white light source. The set of filters works in a white-light correlator.

Many experimental results have been obtained with these techniques. In Figure 15.2 we show one of them. The scene (Figure 15.2a) contains a red traffic stop sign and a green car. Two sets of matched filters for both objects were made with He–Ne and Ar lasers. The experiment was made in real time with a spatial light modulator. In Figure 15.2b we see a black and white picture of the correlation plane where a red peak corresponds to the stop sign and a green peak corresponds to the green car.

(a)

(b)

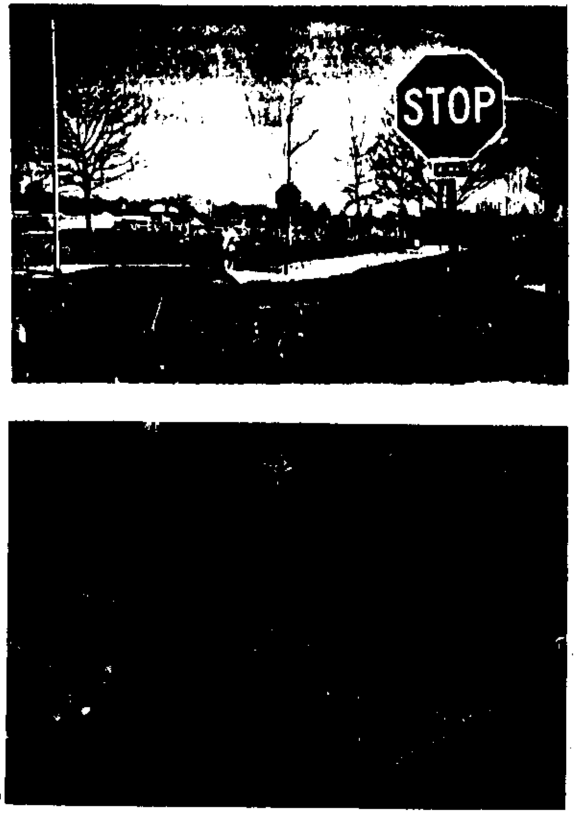

Figure 15.2 (a) Black and white picture of an input scene containing a red stop sign and a green car. (b) Black and white picture of a correlation plane. A red peak (top right) corresponds to the stop and a green peak (bottom left) to the car. (Reproduced from Yu [4] by courtesy of Optical Engineering.)

15.3. MULTICHANNEL COLOUR OBJECT RECOGNITION

It has been pointed out that the introduction of colour may improve the recognition process of colour objects. For this purpose, in any correlator setup the interpretation of the correlation plane for the different wavelengths is important. Each type of recognition problem requires a different strategy. Firstly, we will describe in this section an architecture of multichannel coherent correlator where correlations for the different wavelengths are obtained sequentially.

In this technique the object transparency is given by the transmittances for three wavelengths λ_1, λ_2 and λ_3, that cover as much as possible of the visible spectrum. The amplitude transmittances, $o_{\lambda_i}(x_1, y_1)$ (with $i = 1,2,3$), obtained by successively illuminating the object with these three coherent wavelengths, are called the colour components of the object.

For a polychromatic object, shape and intensity distribution may depend strongly on the illuminating wavelength. It may happen that for two different objects the colour components corresponding to one wavelength are similar for both; then a false alarm can occur when a classical single-channel recognition process is used. In the multichannel process the identification of the target in all three channels considerably reduces the possibility of such false alarms.

Multichannel recognition may be performed by using any correlator. In Figure 15.3 a convergent correlator is shown. Filters matched to the signal g_{λ_i} are used in each channel. The signal g_{λ_i} depends on the problem and on the strategy used. Following VanderLugt's holographic scheme, the classical matched filter (CMF) can be recorded. The term of the filter transmittance that provides the correlation is given by

$$\exp(-i2\pi x_2 \sin\theta/\lambda_i)G^*_{\lambda_i}(x_2/\lambda_i d, y_2/\lambda_i d), \quad i = 1,2,3 \qquad (15.4)$$

where G_{λ_i} is the Fourier transform of g_{λ_i}, (x_2, y_2) are the Cartesian coordinates in the Fourier plane (Figure 15.3), and d and θ are two parameters that correspond to the system used to record the filters, where d is the distance between the object plane and the holographic plate, and θ is the angle between the normal to the holographic plate and the reference beam. For each channel the correlation between the scene and the

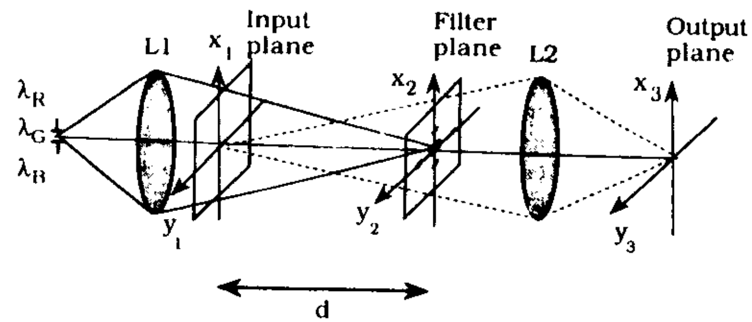

Figure 15.3 Multichannel convergent correlator.

object is obtained when the correlator is illuminated by the same wavelength that is used for recording the filter. It is given by

$$o_{\lambda_i}(x_3,y_3)*g_{\lambda_i}(x_3,y_3), \quad i = 1,2,3 \qquad (15.5)$$

for each wavelength, where (x_3,y_3) represent the Cartesian coordinates in the correlation plane. The position of the correlation does not depend on the wavelength. The object can be recognized by analysing the information that is provided by all three channels.

15.3.1. Different problems, different strategies

We will consider two types of objects. Firstly, we study objects whose geometrical shape and transmittance distribution may change with the illuminating wavelength (Figure 15.4). This problem represents the most general case of objects with different distributions of colours inside the object. Secondly, we consider objects that consist of a colour alphanumeric character on a square background of a different colour (Figure 15.5). This type of object represents polychromatic images with equal contours between colour zones, let us say images that only change the contrast or transmittance values in each zone when illuminated by different wavelengths.

Two problems will be proposed: (1) the recognition of an object as a whole; (2) the recognition of a character on a background regardless of the colour combination of the character and the background [7]. The first problem represents what is considered as the general problem in colour pattern recognition. It can be applied either to objects of the type given in Figure 15.4 or in Figure 15.5. To solve the first problem the filters are matched to the colour components of the object to be recognized. In this way the filters contain both shape and colour information of the target components. The object is recognized when there are intensity maxima at the same point for all the channels (logical operation AND).

To solve the second problem we use two filters in each channel. One of the filters is matched to the character on a dark background, and the other is matched to a dark character on a bright small square. The first one is called the direct filter and the second one the inverse filter. Since the character and the background colours are different, the contrast between them is high in at least one channel. The presence of the character in the scene is detected by the existence of a maximum in any of these correlations (logical operation OR).

Several colour reversal films have been studied [8] as recording media of colour images for the target and the scene. It is shown that the response of the film has a strong influence on the discrimination capability. Among other films the Kodak Ektachrome KM film adapted to tungsten light gave good results and it was chosen for the experiment described in this chapter. The scenes generated for the problems described above were constructed with three colours, red, green and yellow, and then reproduced on the slides. The transmission values of the red, green and yellow zones for the red light of an He–Ne laser and the green light of an argon laser are shown in Table 15.1. The correlation was carried out with only two channels, red and green, without loss of generality, because the blue components for the three colours are very small.

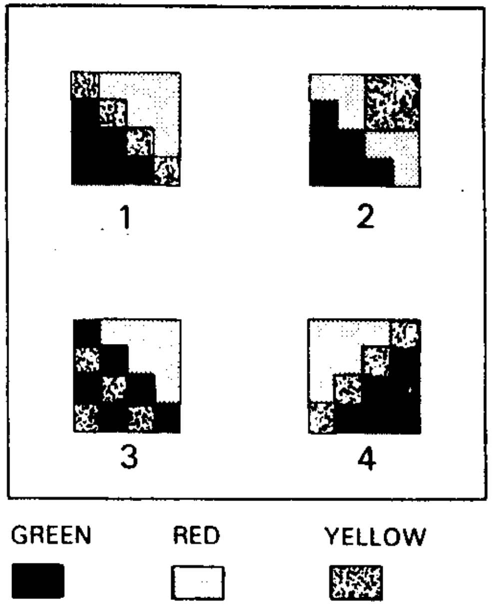

Figure 15.4 *Colour objects.*

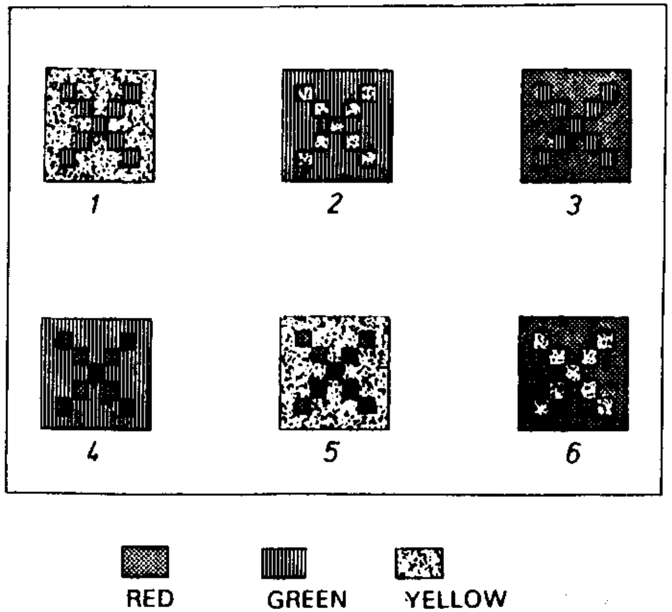

Figure 15.5 *Colour objects.*

15.3.2. Experimental results

The experimental results shown in this section were obtained [9] with the convergent correlator sketched in Figure 15.3. By varying the position of the scene, the scale of its Fourier transform (FT) changes and it matches the dimensions of the filter. Correlation intensity distributions were imaged in the detector of a black and white CCD camera and digitized by means of a frame-grabber.

The phase-only filter (POF) that increases the discrimination capability was applied to colour objects [7–10] and this type of filter is able to recognize the objects with an adequate threshold. To obtain the filters, computer-generated holography techniques were used. We applied the Burckhardt codification method to obtain the phase-only filter codified by means of amplitude variations [11]. A drawing of the filter obtained with a laser printer was photographically reduced. The film introduced in a sandwich gate constituted the filter.

Experimental results were obtained with the objects shown in Figure 15.5. Two scenes were built with these objects: one (scene A) contains objects 1, 2, 3 and 4, and the other one (scene B) contains objects 1, 5, 2 and 6.

The first problem we studied was the recognition of an object as a whole taking into account the shape and the spectral information of the object. In each channel a filter is matched to the corresponding transmittance of object 1 (the object to be recognized). The other objects that are in the scene present the same shape and the only difference is in the colour distribution. In this way we verified the method's capability to distinguish among objects which are different only in the spectral content. Objects represented in Figure 15.4 show differences of shape and colour distribution and their discrimination [10] is easier than for the objects shown in this section.

Figure 15.6 shows 3D plots of the correlation intensity distributions obtained with scenes A and B for both channels. In Table 15.2 the maximum correlation values for each object are listed. These values are normalized in each channel to the value for object 1 (autocorrelation). We suppose that an object is detected in each channel if it gives a value higher than 50% of the maximum. The peaks higher than this threshold value are listed in bold in Table 15.2. Following the strategy described above to solve this problem, an object is identified if it gives simultaneously a peak higher than the threshold in all channels. So, object 1 is identified because it is the only one which fulfils this requirement and no false alarms appear. The correlation values for the other objects can be justified by their transmissions and the borders between different colours (the impulse response of the POF is an edge enhanced version of the original object). To understand these results it is important to consider the amplitude change between the black background and the square, and also between the square and the character. In the red channel, object 3 is very similar to object 1. The transmission of the

Table 15.1 Amplitude transmittances of the colour zones

Colour	λ = 633 nm	λ = 514 nm
Red	0.497	0.158
Yellow	0.660	0.569
Green	0.100	0.473

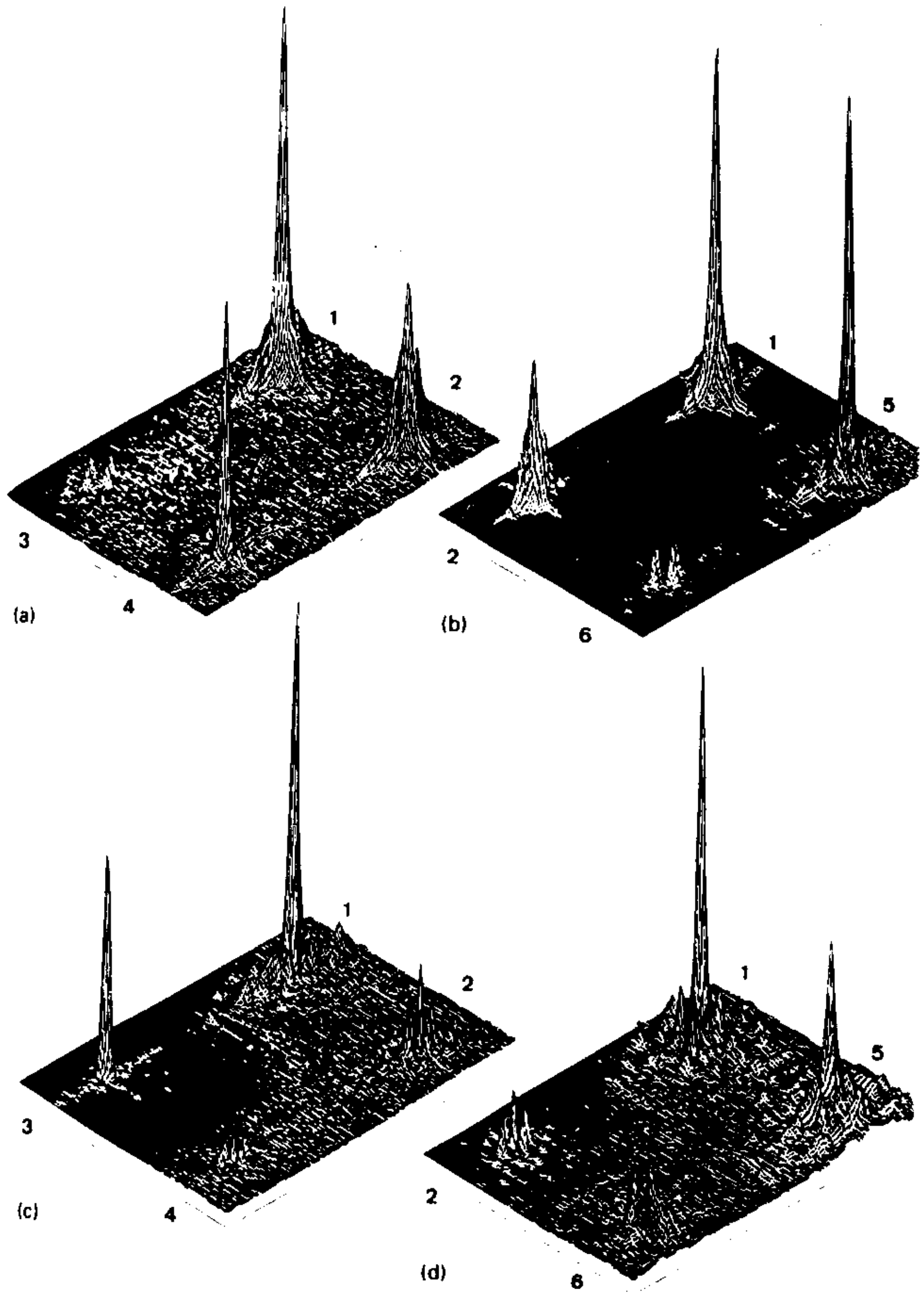

Figure 15.6 *Correlation intensity obtained in the red and green channel with a POF matched to the corresponding transmittance of object 1 and the scenes shown in Figure 15.5: (a), (b) green channel; (c), (d) red channel. (a), (c) scene A; (b), (d) scene B.*

Table 15.2 Values of the correlation peaks obtained with a POF matched to object 1 in the scene of Figure 15.5. Peak values that exceed the threshold value in each row are in bold

Channel	1	2	3	4	5	6
Red	**1**	0.24	**0.59**	0.0[illegible]	0.47	0.14
Green	**1**	0.48	0.00	**0.71**	**1.09**	0.00
AND	Yes	No	No	No	No	No

letter is the same in both objects and the transmission of the square is slightly smaller in object 3 than in object 1 (see Table 15.1). So, the amplitude changes are in the same sense but lower for object 3. Objects 2 and 4 which present the changes in the opposite sense that object 1 give rise to low correlation values.

The second problem was the recognition of a shape (in our case a character) regardless of its colour and the colour of the background [7]. Now two POFs were used in the strategy described above. Table 15.3 shows the intensity values of the correlation maxima for the six objects of Figure 15.5. As in the previous case, all values exceeding the threshold in each channel are considered as detections. It can be seen that all objects are detected in at least one channel, so all of them are recognized.

Other experiments with objects in an extensive background have also been performed. The experimental results are shown in Table 15.4. The recognition of all objects was also achieved. Objects 3 and 4 are the most critical mainly when the background is not large enough (Table 15.3); this problem disappears in the case of a large background (Table 15.4).

15.3.3. Rotation invariance

Correlation based methods have the shift invariant property, i.e., they are able to recognize a target independently of its position, and the location of the correlation peak gives the target position. Nevertheless, by using the CMF or the POF matched to the target it is not possible to detect targets with an orientation different from that to which the filter was matched. In-plane rotations may be modelled analytically and it is possible to expand the target function into a set of orthogonal functions that are invariant to this change. This is given by the circular harmonic (CH) expansion of two-dimensional complex functions [12]. To design the rotation invariant filter it is necessary to select two parameters: the order of the CH and the expansion centre.

Table 15.3 Values of the correlation peaks obtained with POF filters matched to the letter X in direct and inverse contrast. The scene is shown in Figure 15.5

Channel	Contrast	1	2	3	4	5	6
Red	Direct	**0.53**	**1**	0.05	0.26	0.23	0.33
Green	Direct	**0.51**	**0.64**	**0.98**	**0.51**	**0.57**	**1**
Red	Inverse	**1**	0.42	0.47	0.16	0.18	0.07
Green	Inverse	0.22	0.16	0.23	**0.68**	**1**	0.32
OR		Yes	Yes	Yes	Yes	Yes	Yes

Table 15.4 As Table 15.3 but for a scene similar to Figure 15.5 with extensive colour background

Channel	Contrast	1	2	3	4	5	6
Red	Direct	**0.70**	**1**	0.27	0.43	0.30	0.37
Green	Direct	0.17	0.37	**0.80**	0.25	**0.56**	**1**
Red	Inverse	**1**	**0.61**	**0.52**	0.28	**0.55**	0.12
Green	Inverse	0.21	0.16	0.11	**0.94**	**1**	0.36
OR		Yes	Yes	Yes	Yes	Yes	Yes

Rotation invariant colour pattern recognition may be achieved by using the multichannel technique and CH filters [13]. In the multichannel method proposed above, instead of using in each channel a POF matched to different targets it is necessary to use CH filters matched to these targets. Also the POF idea may be generalized to the CH filter. The order of the CH filter and the centre of expansion have to be selected and, in general, may be different in each channel.

15.3.4. Statistical recognition of colour images

Until now we have made the assumption that we are dealing with deterministic images, but usually objects may present variations in shape and in colour. Some variations (like rotation, change of scale) can be described analytically, and recognition can be achieved by using a set of orthogonal functions that are invariant to these changes as we have explained previously (circular harmonic expansion, etc. [12]). On the other hand, there are deformations that have a statistical nature and it is not possible to define functions invariant to these statistical changes. Several methods have been proposed to introduce in the filter the information provided by a training set of images. In general, they are based in the calculation of one or several composite filters. The correlation maxima obtained with these filters are used to build a decision space.

The introduction of colour information in statistical pattern recognition by correlation methods has been proposed by Gu *et al.* [14]. To this end a set of filters is designed for each channel. Thus the dimension of the decision space can be three times as large and colour differences between objects are taken into account. As an example they propose a two class problem. The training set for each class is composed of ten apples (red for class one, and green for class two). They show that better discrimination is achieved when the spectral information is considered.

15.3.5. Polychromatic neural network

Artificial neural networks (ANN) have proved to be a useful tool for pattern recognition and for associative memories which can be implemented optically. As in the field of optical pattern recognition, most of the work was carried out with monochromatic information. The ANN concept may also be extended to polychromatic information. Recently, Yu *et al.* [15] have presented a polychromatic neural network implemented with liquid crystal televisions. The introduction of colour in ANN may be useful for two purposes. On the one hand, it makes possible the analysis of colour images, where the colour information may improve the classification process. On the other hand, the capacity of the polychromatic neural net can be increased three times.

15.4. CHROMATICITY DISTRIBUTIONS

Until now we have described colour images in an RGB colour representation system. This choice has two advantages. Firstly, if we illuminate a transparency with three monochromatic lights (laser beams), only the information provided by the corresponding amplitude transmittances for the three wavelengths is available and we suppose that this information is enough. However, the development of colour image acquisition and display systems makes available inexpensive good quality colour images. Many of these systems use an RGB decomposition of colour to record and to display images, so we have direct access to this information. However, this decomposition of colour, that is very convenient for display purposes, may not be so convenient for recognition problems. Badiqué *et al.* [16,17] have proposed combining the information provided by the three RGB channels in order to obtain better discrimination and sharper peaks.

We generalize here the proposal of Badiqué *et al.* [17]. A general linear chromatic coordinate change may be defined as a change of the coordinates from the RGB system to another (l,m,n) system (Figure 15.7). This change of coordinates is determined by a matrix $\boldsymbol{\alpha}$:

$$\begin{pmatrix} f'_l \\ f'_m \\ f'_n \end{pmatrix} = \begin{pmatrix} \alpha_{lr} & \alpha_{lg} & \alpha_{lb} \\ \alpha_{mr} & \alpha_{mg} & \alpha_{mb} \\ \alpha_{nr} & \alpha_{ng} & \alpha_{nb} \end{pmatrix} \begin{pmatrix} f_r \\ f_g \\ f_b \end{pmatrix} \tag{15.6}$$

From these components it is possible to define a new function by the expression

$$f(\mathbf{r}) = \sum_i \beta_i f'_i(\mathbf{r}) \tag{15.7}$$

where β_i is a complex number and it is the ith component of a vector $\boldsymbol{\beta}$. So the correlation between two images $f(\mathbf{r})$ and $g(\mathbf{r})$ in this new system is given by

$$C_{fg} = f(\mathbf{r}) * g(\mathbf{r}) = \sum_i \sum_j \beta_i \beta_j^* (f'_i(\mathbf{r}) * g'_j(\mathbf{r})) \tag{15.8}$$

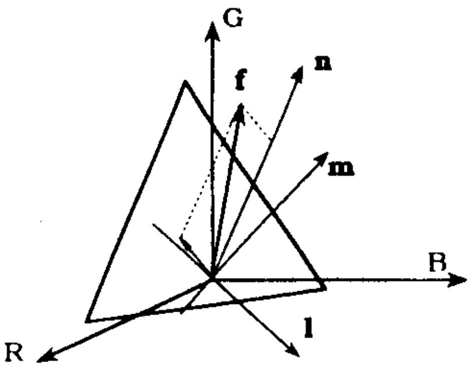

Figure 15.7 *General chromatic coordinate change from an RGB system to another (l,m,n) system.*

Taking into account equation (15.6) the correlation C_{fg} may be expressed as

$$C_{fg} = \sum_l \sum_m s_{lm} (f_l(\mathbf{r}) * g_m(\mathbf{r})) \tag{15.9}$$

$$s_{lm} = \sum_i \sum_j \beta_i \alpha_{il} \beta_j^* \alpha_{jm}^* \tag{15.10}$$

Equation (15.9) tells us that the correlation C_{fg} is a linear combination of the cross-correlations between the components of the original system. This is a consequence of the utilization only of linear operations. The change proposed in [17] can be obtained with this general formulation. An optimization of the coordinate change may also be formulated in order to increase discrimination capabilities [17]. The parameters to be optimized are the components of matrix $\boldsymbol{\alpha}$ and vector $\boldsymbol{\beta}$.

15.5. SOME FINAL REMARKS

We have described several architectures for colour pattern recognition. Some problems are also stated as examples of the very large number of different questions that may appear in image recognition when colour information is introduced. One of them explains the general case and the other is related to automatic reading. With the description of these architectures we have not given a proper summary of all different approaches one can find in the literature. Nevertheless we wanted to point out how the introduction of colour can help in pattern recognition. Many questions related to colour information are still open and in this section we will comment on some of them.

A normal human eye distinguishes very well between different colours even if they are quite similar. Thus if there are small differences in the colour distributions of two objects, identification is easy for a human being, but it is not an easy problem to solve using a machine. However, colour constancy is a problem not only in colorimetry but also in robotics. For instance a problem appears when a robot advances and the illumination changes.

When an image is captured by a camera it can be useful to modify the colour information to be more suitable for an automatic pattern recognition process. In a real time correlator, the transmittance response of the spatial light modulators has to be taken into account. In an architecture such as the multichannel correlator described in Section 15.3, the SLM is illuminated with monochromatic light and the information from the different channels is introduced sequentially. The information in each channel could be enhanced separately. Other channels outside the visible spectrum could also be introduced and would enlarge the processing possibilities.

The correlation method suffers in each channel the same problems as in the case of monochromatic objects. If two objects show similar amplitude distribution in a channel they will give similar correlations. Thus the utilization of different kinds of filters with different discrimination capability could be studied. The phase only filter has been used in obtaining the results given here to improve the discrimination. Rotation invariance and statistical pattern recognition have also been described. Some properties of other filters for monochromatic processing can also be applied to colour image recognition.

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Correlation methods in polychromatic objects recognition. Application of lithographic filters.

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ABSTRACT

A review of the multichannel correlation methods applied to discriminate colour objects with the logical operation AND is presented. The effects of the colour CCD camera as the acquisition system is studied. A preprocessing method is proposed to increase the discrimination. The generation of the filters is improved by applying lithographic techniques. Finally an approach of the optimal filter proposed by Yaroslavsky is applied to each channel in the correlation process. Computer and experimental results are given.

1. INTRODUCTION

In the last decades there is an increasing interest in introducing the colour in image processing[1] and particularly in optical pattern recognition[2]. Thus, the objects are discriminated not only from their geometrical shape but also according to their colour distribution. Several authors[3-6] have proposed colour image recognition by matched filtering taking into account the shape and the spectral information of the object. This permits an improvement in the discrimination sensitivity. The introduction of colour gives an additional information. For a colour object both shape and intensity distribution may depend on the illuminating wavelength used in an optical correlator. The similarity measure is performed by the correlation of the scene with the target. Optically the correlation is obtained by imaging the Fourier transform of the scene on a matched filter which contains the information of the Fourier transform of the target.

A digital formulation for the correlation of colour objects was given by Badiqué et al[7,8]. They proposed a generalized plane to optimize the sharpness of the correlation peak. Yamaba and Miyake[9] have proposed for digital images a method based on the colour human vision models.

We studied[10,11] a multichannel technique where the polychromatic object is decomposed in three monochromatic channels and the information obtained by the correlation in each channel gives the final recognition. We have obtained experimental results[12] in an optical implementation of the multichannel recognition procedure. Polychromatic objects are detected by means of optical synthesis of improved classical matched filters based on the holographic matched filters of Vander Lugt[13].

In this contribution we present in section 2 the optical set up for the experiments in multichannel correlation and some experimental results with the phase only filter (POF). The first step in the recognition problem is the capture of the scene to be analyzed. This process has a large influence in the recognition because colours may be changed and the information in each channel is altered. Some studies on the influence of the features of different CCD colour cameras have been carried out and some results are given in section 3. The use of some kind of preprocessing may improve the behavior of the recognition process. We have tested edge enhancement in each channel and also the combination of the information of the three channels. In section 4 we show some results with preprocessing methods. To generate the filter transmittance it is necessary to apply techniques of computer generated holograms. We have used different technologies

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to obtain the filters. They mainly differ in the resolution and the cost. High resolution polygraphic printers and lithography are used and compared in section 5. The key element in optical pattern recognition by correlation is the design of the filter. Different designs have been proposed by many authors to improve some characteristics of the method, like the signal to noise ratio, discrimination capability, light efficiency, etc. In section 6 the optimal filter proposed by Yaroslavsky[14] has also been generated by lithography and it is used in colour pattern recognition.

2.MULTICHANNEL CORRELATION

2.1 Optical setup.

The input scene is introduced in a convergent correlator (figure 1) in plane $P_1(x,y)$. If it is a colour slide, three wavelengths $(\lambda_1,\lambda_2,\lambda_3)$, distributed in the visible spectrum, illuminate the scene and the correlations are performed successively. If the scene is captured by a colour CCD camera, the matrixes in the three channels are displayed successively in a spatial light modulator placed in plane $P_1(x,y)$ and the optical correlator may work with the same wavelength for the three channels and in real time.

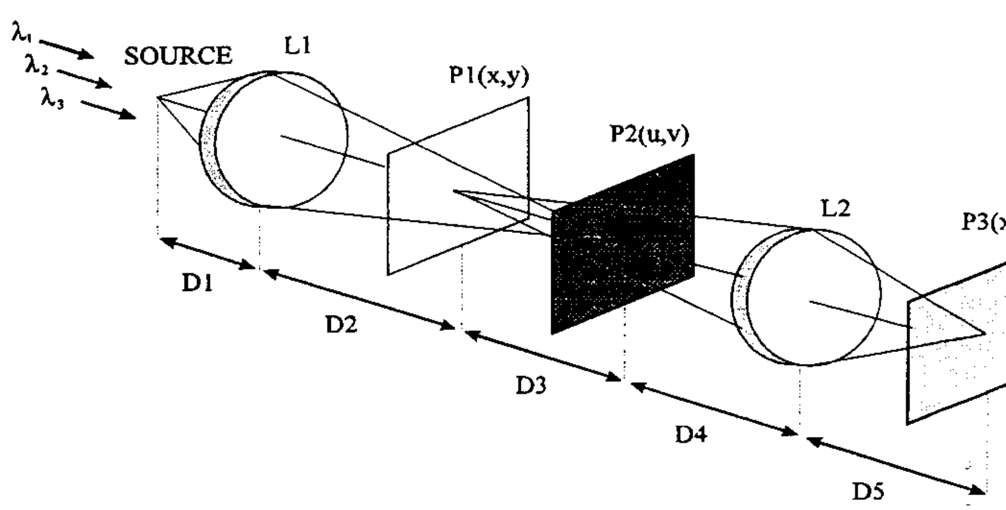

Figure 1. Multichannel convergent correlator.

The filters matched to the target for each channel $h_{\lambda i}$ will depend on the problem to be solved and the strategy to be followed[15]. The filter is placed in the correlator (figure 1) in the plane $P_2(u,v)$, and in the correlation plane $P_3(x',y')$ we obtain for each monochromatic channel the following function

$$c_{\lambda i}(x',y') = K\,\psi_{\lambda i}\left(x',y';d_5-\frac{d_5^2}{d_4+d_5-f_2}\right)\iint G_{\lambda i}(d_3u,d_3v)H^*_{\lambda i}(u,v)\,exp\left[jk\frac{-d_4d_5}{d_4+d_5-f_2}(ux'+vy')\right]du\,dv, \quad (1)$$

where K is a constant and $\psi_{\lambda i}$ is a function defined by

$$\psi_{\lambda}(x,y;f) = exp\left[j\frac{\pi f}{\lambda}(x^2+y^2)\right]. \quad (2)$$

Apart from this phase factor, (1) is the Fourier Transform of the product of functions $G(d_3u,d_4v)$ and $H^*(u,v)$. The values d_i are the inverse of the distances D_i described in figure 1. f_2 is the focal length of the achromatic lens L_2.

$G_{\lambda i}(u,v)$ represents the Fourier Transform of the scene $g_{\lambda i}(x,y)$ and the scale may be changed by modifying the distance D_3. In this way the Fourier Transform of the scene is scaled in accordance with the filter size. $H^*_{\lambda i}(u,v)$ represents the filter function. From (1) we see that in plane P_6 we obtain the correlation between the scene $g_{\lambda i}(x,y)$ and the target $h_{\lambda i}(x,y)$ in each monochromatic channel.

2.2. Results.

The main problem which appears in colour pattern recognuon is the discrimination of an object as a whole among other objects. Along this contribution we will consider the scenes shown in figure 2 and figure 3. The objects in figure 2 present different shape and colour distribution. In figure 3 the objects show the same contours but a different combination of colors.

When the multichannel correlation is carried out, the filter used in each channel is matched to the target transmittance for the illuminating wavelength of the corresponding channel $h_{\lambda i}(x,y)$. We use three channels to reduce the false alarms that may occur when a classical single-channel recognition process is used. These false alarms are produced when different polychromatic objects present a similar amplitude distribution under a given monochromatic illumination. In the multichannel process the identification of the target is carried out by the verification of a correlation peak in all the channels. A given threshold, normally 50% is applied to the different correlation planes and the logical operation AND gives the decision. We pointed out [11] that for the type of objects corresponding to scene 2 the classical matched filter (CMF) does not provide enough discrimination capability whereas the use of phase-only filters (POFs) does.

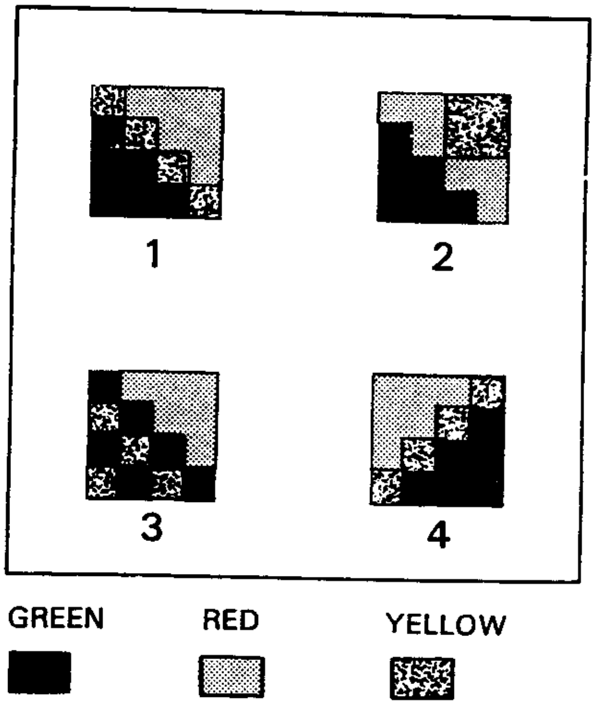

Figure 2. Scene

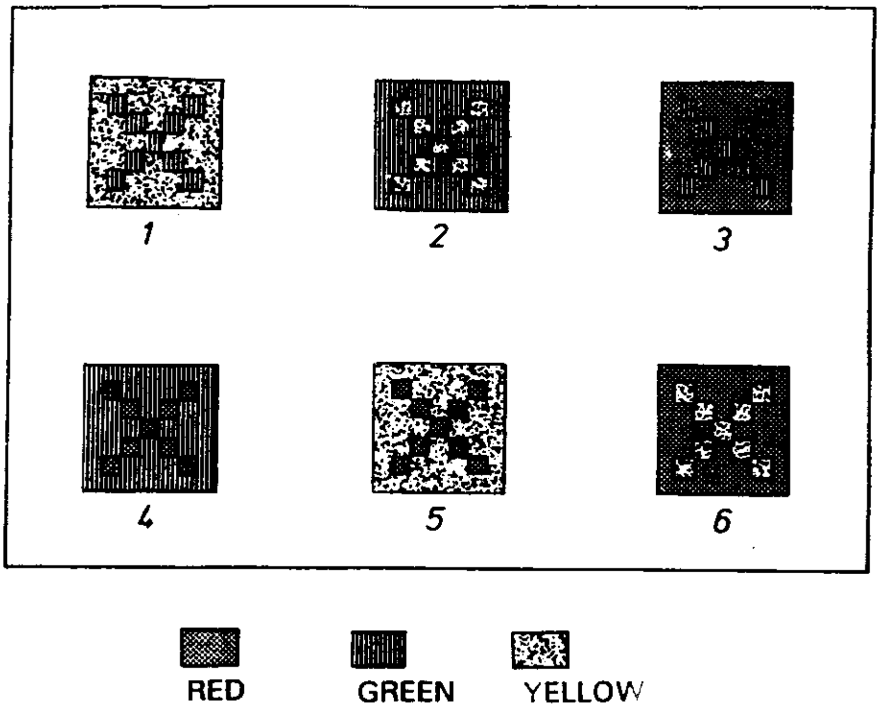

Figure 3. Scene.

Without loss of generalization the objects in figures 2 and 3 consist on three colours: red, green and yellow. In a previous study we gave the transmission of different photographic films for these colour papers[16], and we studied the conditions which give better results in pattern recognition. Table (1) shows the transmission values for a slide which corresponds to the red, yellow and green zones for the red coherent illuminating wavelength (He-Ne laser) and for the green coherent illuminating wavelength (Ar laser). The transmission for blue illuminant is negligible. So we will give our results for only two channels.

Colour	λ=633 nm (He-Ne laser)	λ=514 nm (Ar laser)
Red	0.497	0.158
Yellow	0.660	0.569
Green	0.100	0.473

Table 1. Amplitude transmission values for the red, yellow and green zones.

We will show here experimental results obtained with the objects shown in figure 3. Two scenes were built with these objects: one (scene A) contains objects 1,2,3, and 4, and the other (scene B) contains objects 1,2,5 and 6. We applied the Burckhardt's codification method to obtain the phase only filter codified by means of amplitude variations[17]. A drawing of the filter obtained with a laser printer was photographically reduced. The film introduced in a sandwich gate constituted the filter. In each channel a filter is matched to the corresponding transmittance of object 1 (the object to be recognized). Figure 4 shows 3D plots of the correlation intensity distributions obtained with scene A and B for both channels. In table 2 the maximum correlation values for each object are listed. These values are normalized in each channel to the value for the object 1 (auto correlation). We suppose that an object is detected in each channel if it gives a value higher than 50% of the maximum. The peaks higher than this threshold value are bold faced in table 2. Following the strategy described above to solve this problem, an object is identified if it gives simultaneously a peak higher than the threshold in all channels. So, object 1 is identified because it is the only one which fulfills this requirement and no false alarms appear.

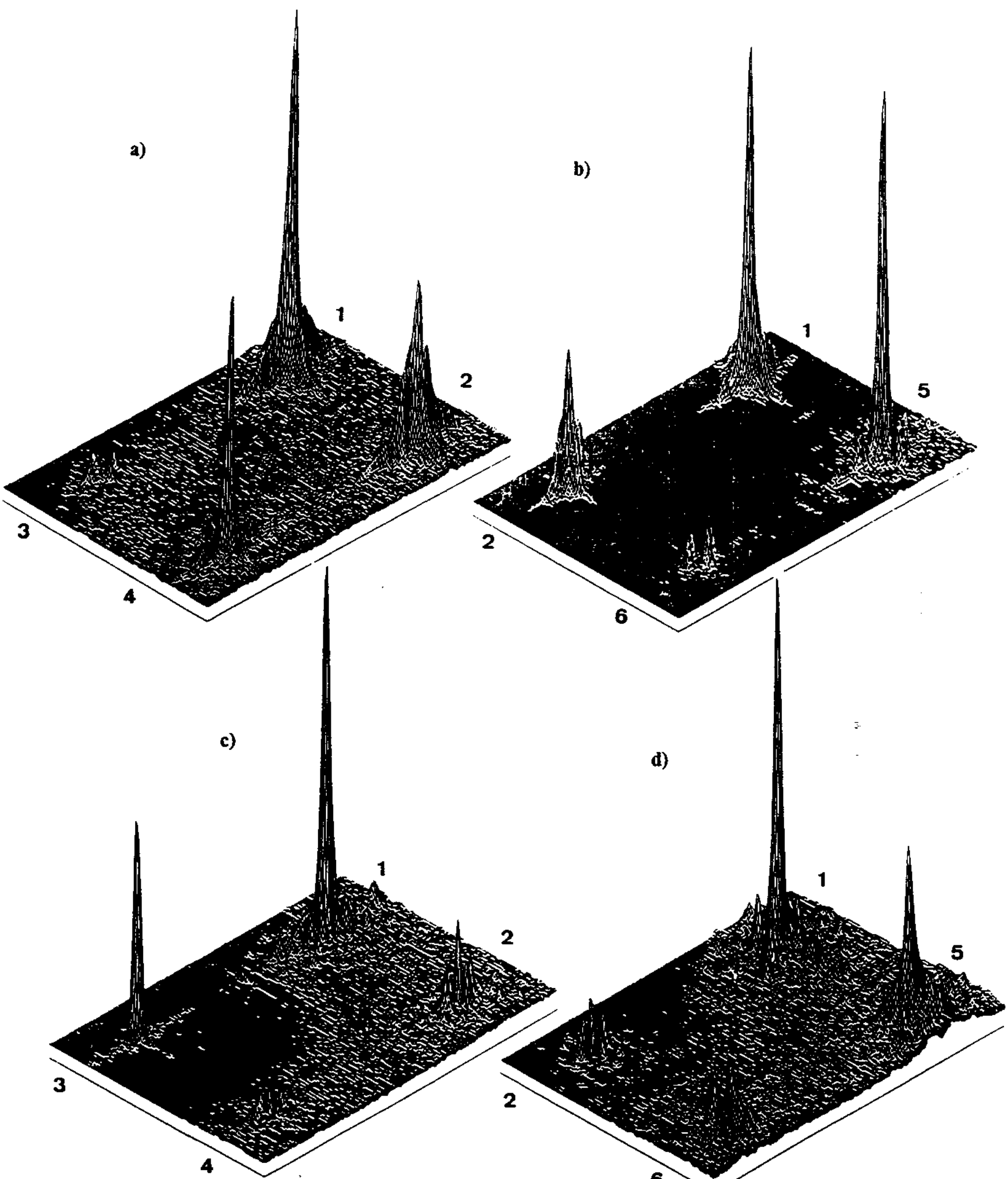

Figure 4. 3D plots of the correlation intensity distributions obtained with POF matched to object 1. Scene A (a and c) and scene B (b and d) from figure 3. a) and b) Green channel; c) and d) Red channel.

Channel	O.1	O.2	O.3	O.4	O.5	O.6
Red	**1.00**	0.24	**0.59**	0.07	0.47	0.14
Green	**1.00**	0.48	0.00	**0.71**	**1.09**	0.00
AND	**YES**	NO	NO	NO	NO	NO

Table 2. *Values of the correlation peaks obtained with POFs matched to object 1.*

3. INTRODUCTION OF THE SCENE BY AN ACQUISITION SYSTEM

The use of colour slides to introduce the scene has been analyzed previously[16]. In real time recognition systems, the original scene is captured by a CCD camera, digitized and displayed on a SLM[18]. Recently Yu et al[19] have proposed the application of colour Liquid-crystal TV in a joint-transform correlator for polychromatic image identification. In this section we analyze the use of a CCD colour camera for image acquisition applied to optical recognition of colour objects. The spectral and spatial information of the captured image is stored in three matrixes R (red), G (green) and B (blue) which can be processed separately following the multichannel correlation method. Varying the acquisition system parameters such as colour balance, gain and offset, image information also changes because contrast variations are introduced in the RGB matrixes.

We considered one scene with the objects 1, 3, 4 and 6 of figure 3, and the object 3 is the target to be recognized. The original scene was illuminated with almost uniform fluorescent illumination of 5000 K. It was captured by a camera with automatic colour balance. A colour CCD camera with 3 detectors was employed. In table 3 we present the most significant results obtained for a gain value of 240 and offset values of 140 and 205. Phase only filters matched to the object 3 in the matrixes obtained with gain 240 and offset 140 have been generated to simulate numerically the recognition process. The POF has been selected because of its high discrimination capability when it is applied to these kind of objects[11]. We observe that the recognition of object 3 without false alarms is obtained in both cases.

a) Offset 140

Ch	O.1	O.3	O.4	O.6
R	**1.40**	**1.00**	0.07	0.14
G	0.26	**1.00**	0.21	**1.35**
AND	NO	**YES**	NO	NO

b) Offset 205

Ch	O.1	O.3	O.4	O.6
R	**1.83**	**1.00**	0.09	0.15
G	0.23	**1.00**	0.24	**1.45**
AND	NO	**YES**	NO	NO

Table 3. *Correlations obtained with the images captured with a colour CCD camera with three detectors. Gain value 240.*

4. PREPROCESSING FOR COLOUR PATTERN RECOGNITION.

Preprocessing has been proven to be efficient in some cases in pattern recognition. Lowenthal and Belvaux[20] proposed the correlation between the derivative of the scene and the target. These operations are applied in the Fourier plane, by using a filter with a given transmission. In this section we study the behavior of a preprocessing applied to colour pattern recognition in each channel in order to improve the discrimination capability. The preprocessing is based in edge enhancement of the colour sectors in the target and in the scene by using a linear filter based on the Laplacian operator. To increase the recognition capability of the system, a binarization is applied to the three components after the edge detection. This technique is introduced to avoid the contrast variation, and it can be applied to discriminate a target when it presents a different contours. The Laplacian mask (L) is used for the detection of isolated points and the contours. Let $f_{\lambda i}(x,y)$ denote one of the three colour signals obtained in a multichannel procedure. And let $L[f_{\lambda i}](x,y)$ be the resulting preprocessed signal. The binarization is used for choosing a single edge, and, this binarization is given by the following formula:

$$B\langle L[f_{\lambda_i}](x,y)\rangle = \begin{cases} 1 & if \quad L[f_{\lambda_i}](x,y) \geq T \\ 0 & if \quad L[f_{\lambda_i}](x,y) \prec T \end{cases} \tag{3}$$

where T means a threshold value for the binarization. The scene we consider is given in figure 2. With the conventional phase only filter, the AND operation is applied to correlation planes to detect the target and to avoid false alarms given by similar objects in each channel. By using only the Laplacian, the discrimination capability of the correlation procedure is improved with respect to the correlation with the POF. The operation AND has also been applied to avoid the false detection in each channel. The information of a single channel is insufficient for the detection problem in colour pattern recognition. Hence, we suggest to apply the binarization given by the equation 3 at the components preprocessed by the Laplacian in order to improve the discrimination using only the information of a single channel. In table (4) we summarize the results of the discrimination with POF, with the preprocessing with the Laplacian and with the binarized Laplacian using POF. The 3D plot of correlation plane for red and green channels are given in figures (5) and (6). Figures (5a) and (5b) show the results obtained with POF in the green and red channels, respectively. Figures (6a) and (6b) show the correlation planes obtained with POF using the preprocessing based on the binarization of the components preprocessed by the Laplacian in the green and red channels, respectively. From the results of table (4) and figures (5,6) it is shown that with POF and with Laplacian operator, the object 1 is not recognized because some ambiguity exists in each channel. The application of AND operation is necessary to recognize the target, and the information of the two channels is used. Whereas when the method with the binarization of the preprocessed component is applied, the detection is much easier and, with an appropriate threshold, the recognition of the object 1 is achieved in each single channel.

		Object 1	Object 2	Object 3	Object 4
POF	RED	1	0.92	0.25	0.25
	GREEN	1	0.28	0.90	0.17
LAPLACIAN	RED	1	0.89	0.28	0.23
	GREEN	1	0.24	0.87	0.14
Binarization of LAPLACIAN	RED	1	0.49	0.23	0.12
	GREEN	1	0.14	0.33	0.12

Table 4. *The discrimination capability obtained by preprocessing methods.*

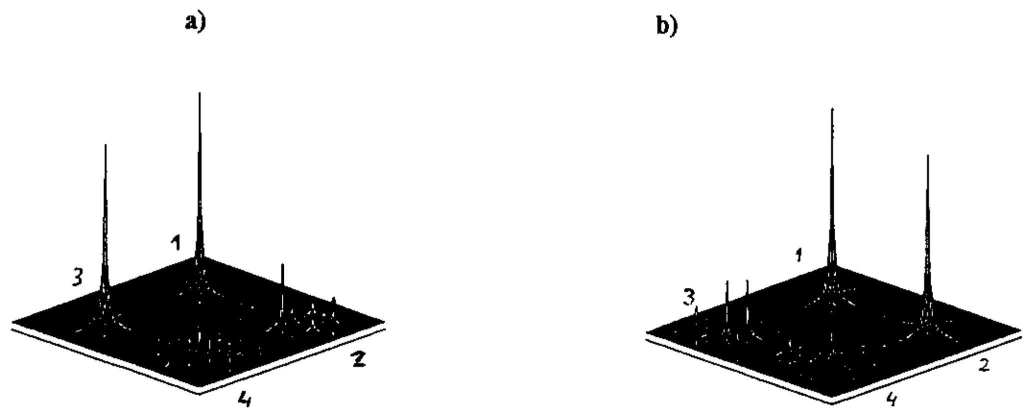

Fig. 5. *Correlation intensity with a POF for the recognition of object 1 in the scene of Figure 2: a) Green channel; b) Red channel.*

a) b)

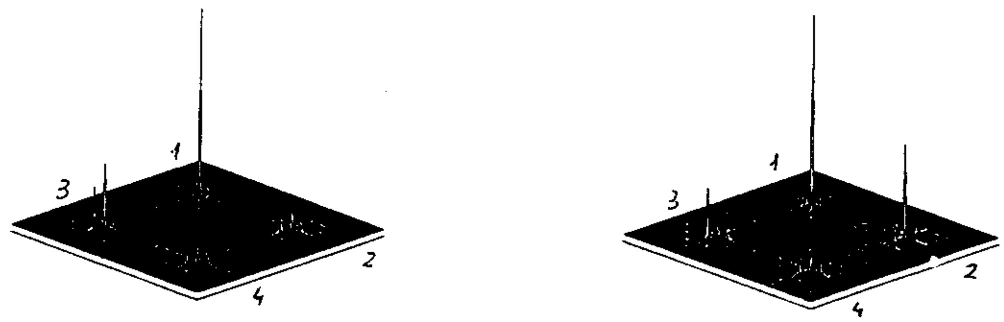

Fig. 6. Correlation intensity with a binarized Laplacian preprocessing using POF for the recognition of object 1 in the scene of Figure 2: a) Green channel; b) Red channel.

5. LITHOGRAPHIC FILTERS FOR PATTERN RECOGNITION.

Optical correlators for pattern recognition need a hologram to be used as a complex filter in the Fourier plane. Some filters, like classical matched filter proposed by Vander Lugt can be obtained by optical holography, but many other filters use mathematical operations that can not be obtained optically and must be calculated using digital holographic techniques.

The digital hologram obtained by computer must be implemented in a physical medium to be used in an optical correlator. The most common media to register the filter are amplitude media, as photographic film, that can only display light intensity distributions. Thus, complex distributions must be implemented using codification methods. These codification methods are very sensitive to spatial resolution of the output device which prints the computer generated hologram.

Laser printer devices have enough resolution to implement computer generated holograms that require low number of gray levels and low resolution. They are not expensive and easily available, but have low spatial resolution. Lithographic techniques, that are used in microelectronics can be used to produce diffractive elements. These techniques are expensive and not easily available, but they have a high spatial resolution. We have codified the computer generated holograms by using the detour phase method[21]. The amplitude distribution is controlled by the size of a rectangular aperture, while the phase distribution is controlled by its position. We have used a high resolution laser writer, Linotronic type, with a resolution of 3251 dots per inch (much greater than usual laser printers with 300-600 dots per inch) and an ultraviolet lithographic technique, that can produce rectangular apertures up to a size of 5 μm with a precision in the position of 0.25 μm.

Figure 7 shows the magnified images of two holograms. The first is obtained by drawing an image of the computer generated hologram by Linotronic laser writer. We can see that the rectangular apertures of the detour phase hologram have not very well defined contours. However, in the second one, obtained by lithographic technique, we can see a great improvement in the contours of the rectangles. In addition, the higher spatial resolution of lithography permits to control more quantization levels in phase and amplitude distributions resulting in less quantization errors.

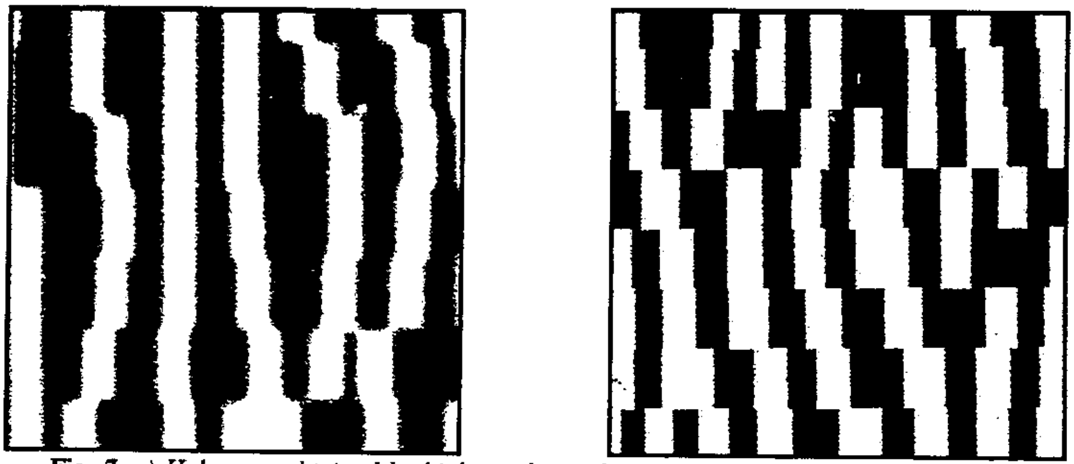

Fig. 7. a) Hologram obtained by high resolution laser printer. b) Hologram obtained by lithographic technique.

We have codified a phase only filter matched to gray tone objects and we have made optical correlation using as an input scene an image with two similar objects. We have measured the discrimination capability of the same phase only filter built with these two techniques. The Linotronic one gives a cross-correlation peak of a 31% of the auto-correlation peak, while with the lithographic filter it is a 20%. Thus, an important improvement in the correlation results are obtained when we use a filter produced by high spatial resolution devices as lithographic ones.

6. OPTIMAL FILTER.

The synthesis of an optimal filter in terms of reliability of peak localization was proposed by Yaroslavsky[14] and it was called Optimal Filter (OF). This filter is optimized in terms of the ratio: peak response to standard deviation of the signals for the objects to be rejected. According to this criteria the filter amplitude in the Fourier domain for a monochromatic target is given by:

$$H = \frac{X_o^*}{AV_{SN}\left|X_{rj}\right|^2}, \tag{4}$$

where X_0^* is the complex conjugate spectrum of the given object, X_{rj} is the spectrum of the objects to be rejected and AV_{SN} represents spectrum average over realizations of sensor noise.

If the similarity between the target and the different objects which may appear in a monochromatic scene is taken into account, the central cross-correlation was introduced[22] in the coefficients of the OF design as follows

$$c_j = X_j^T H, \tag{5}$$

where c_j is the central cross-correlation between the wrong objects x_j and the filter h. Then the so called OF_4 is given by

$$H = \frac{X_i^*}{\sum_{j\neq i} c_j \left|X_j\right|^2}. \tag{6}$$

And that filter is obtained by following an iterative method. A previous study for binary objects is made in Ref. 22. From those results we concluded that the most discriminant filter among POF, OF's and Minimum Average Correlation Energy Filter (MACE)[23] for binary multi-object scenes is the OF_4. For such a reason we use the OF_4 for colour pattern recognition.

Ch	O.1	O.2	O.3	O.4	O.5	O.6
R	**1.00**	0.27	**0.52**	0.12	0.33	0.04
G	**1.00**	**0.62**	0.06	**0.76**	**1.13**	0.09
AND	**YES**	NO	NO	NO	NO	NO

***Table** 5. Correlations obtained with Optimal Filter (OF_4)*

The objects we introduce in the scene are shown in figure 3. The filters are matched to object 1. By the results obtained with the POF, it can be seen that the highest cross-correlation peak appears for object 5. So, taking into account this similarity, the OF_4 is built by introducing the power spectrum of the object 5 in the denominator, and the power spectrum of object 1 in the numerator. The target is recognized by applying the logical operation AND. The results obtained digitally and optically agree and they are shown in table 5. The optimal filter is built by lithographic technique. We consider a threshold of 50% of the maximum in each channel. Only object 1 gives correlation peaks higher than the threshold in both channels. These results show the capability of the optimal filter for colour pattern recognition.

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MATCHED FILTER AND PHASE ONLY FILTER PERFORMANCE IN COLOUR IMAGE RECOGNITION

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A multichannel colour image recognition technique is developed. Classical matched filters and phase only filters are studied. The discrimination capabilities of these filters are compared by submitting the process to two different types of tests: objects with shape and colour variation and objects with colour variation only. For the latter objects the discrimination of a given pattern can only be achieved with the use of phase only filters.

1. Introduction

Since the introduction of the matched spatial filter [1], multiple applications of correlation detection have been developed. Although most of them deal with the shape information of the test, they do not consider the colour information.

Several authors [2–5] propose colour image recognition by matched filtering taking into account the shape and the spectral information of the object. This permits an improvement in the discrimination sensitivity.

Case [6] uses the wavelength-multiplexed matched spatial filters in an incoherent optical pattern recognition system. Colour-coded correlation responses are produced to recognize several objects simultaneously. Mu et al. [7] developed a theoretical and experimental analysis of colour image pattern recognition by multiwavelength Fresnel holographic filter. In this technique the filter alignment is less stringent.

The design of spatial light modulators leads to the real-time optical pattern recognition. The use of a magnetooptic device such as a binary spatial light modulator for colour object identification is proposed by Javidi et al. [8].

A formulation for digital colour image correlation has been recently proposed by Badique et al. [9,10]. They found an optical generalized colour plane to optimize the correlation peak sharpness.

It has been proved that the phase only filters POF carry more information about the object than the amplitude filters. Horner and Gianino [11] showed by computer simulation and using alphanumerical characters that the POF discriminate better and are more efficient than the classical matched filter CMF. Nevertheless, the signal no noise ratio is higher for the CMF. Kumar and Bahri [12] introduced the notion of optimal phase only filter to improve signal to noise ratio. Chalasinska-Macukow and Nitka [13] presented an optical and digital analysis of the discrimination capability of the POF and they compared them with the high pass matched spatial filter.

In this paper, we propose a multi-channel correlation process to recognize the coloured object by their identification in several monochromatic channels. When objects with different spatial colour distribution are illuminated by a monochromatic beam, they may present similar amplitude distribution. The discrimination between such objects become more difficult and some false alarms appear in a CMF correlation.

CMF and POF are studied. In both cases several filters matched to the object transmittance for each wavelength are designed. The coincidence of the peak correlation in the different channels allows us to rec-

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ognize the object avoiding the ambiguities produced in a monochromatic correlator.

We studied two different object types. The first objects differed in shape and colour distribution. The second type presented the same shape but with a different colour combination. The performance of the CMF and the POF were studied with these two types of objects.

2. Colour correlation

In pattern recognition, when polychromatic objects are considered, the amplitude transmittances characterizing the objects $h_\lambda(x_1, y_1)$, depend on the illumination wavelength λ. Nevertheless, distinct objects can present similar amplitude distributions when illuminated with a determined wavelength, thus giving rise to possible false alarms in the recognition process.

To detect a colour object in a polychromatic scene we shall use different filters matched to the object transmittance for varying wavelengths. In this way we avoid ambiguities in the detection. CMF and POF will be used.

To record a filter, the object is placed at the front focal plane of an achromatic system and a plane reference wave is added making an angle θ with the normal to the photographic plate. If the wavelength used is λ_1, the filter transmittance which will provide the correlation term may be written [14] as

$$\exp[-i2\pi x_3(\sin\theta)/\lambda_1]\, H^*_{\lambda_1}(x_3/\lambda_1 f; y_3/\lambda_1 f)\,, \tag{1}$$

where H_{λ_1} is the Fourier transform of $h_{\lambda_1}(x_1, y_1)$ and f is the focal length of the transforming lens system.

The correlation is performed with a 4f correlator. If the scene is illuminated by the same wavelength that is used to obtain the filter, the correlation will be called direct correlation. When the scene coincides with the test this term is given by

$$h_{\lambda_1}(x_c, y_c)^* \, h_{\lambda_1}(x_c, y_c)\,. \tag{2}$$

It is centered at the point $x_c = -f\sin\theta$ and $y_c = 0$, where x_c, y_c represent the cartesian coordinates in the correlation plane. As may be seen, the position of the correlation peak does not depend on the wavelength.

On the contrary, when the scene is illuminated by a wavelength, λ_2, other than the one used to record the filter, the correlation will be called crossed correlation. When the scene coincides with the test, this term is given by

$$h_{\lambda_2}\left(\frac{\lambda_2}{\lambda_1} x_c; \frac{\lambda_2}{\lambda_1} y_c\right)^* h_{\lambda_1}(x_c, y_c)\,. \tag{3}$$

It is centered at the point $x_c = -(\lambda_1/\lambda_2) f\sin\theta$ and $y_c = 0$. Now, the position of this point depends on the wavelengths used during the recording and the detection processes. By a proper choice of the parameters f, θ and of the object size, in function of the different wavelengths, the distinct crossed correlations come out separately from the direct correlation. For instance, working with a 4f correlator, considering a square scene of 12 mm side and a signal to be recognized of 4 mm, the minimum separation between direct and crossed correlations should be 20 mm. Using the wavelengths $\lambda_1 = 514$ nm (Ar laser line) and $\lambda_2 = 633$ nm (HeNe laser line), and taking for the 4f correlator a focal length of 200 mm, choosing an angle θ greater than 32.5° for the plane reference wave assures the separation of the different terms.

However, even by using the previous procedure, the ambiguities in the detection are not always avoided. We shall show an example of this behaviour in the next section.

Thus, taking into account the well known properties of the POF to improve the discrimination between similar objects, we, next, introduce this type of filter to improve the discrimination capability of the procedure proposed in this work. For the object $\lambda_1(x_1, y_1)$, the CMF may be written as

$$\mathscr{F}^*\{h_{\lambda_1}(x_1, y_1)\} = H^*_{\lambda_1}(x_3/\lambda_1 f; y_3/\lambda_1 f)\,, \tag{4}$$

where $\mathscr{F}$ represents the Fourier transform operator. The functions h_{λ_1} and H_{λ_1} are in general complex. H_{λ_1} can be represented as

$$H_{\lambda_1}(x_3/\lambda_1 f; y_3/\lambda_1 f) = |H_{\lambda_1}|\, \exp[i\phi(x_3/\lambda_1 f; y_3/\lambda_1 f)]\,. \tag{5}$$

The phase only filter, $H^{\varphi}_{\lambda_1}(x_3/\lambda_1 f; y_3/\lambda_1 f)$, is given as

$$H^p_{\lambda_1}(x_3/\lambda_1 f; y_3/\lambda_1 f)$$
$$= \exp[-i\phi x_3/\lambda_1 f; y_3/\lambda_1 f] , \quad (6)$$

obtained by setting the modulus $|H_{\lambda_1}|$ equal to unity. According to Horner and Leger [15], a simple model of a POF is given by a CMF associated with an additional amplitude only filter. The transmittance of this additional filter should be equal to $|H_{\lambda_1}|^{-1}$, and can be performed by recording the intensity of the Fourier transform function of the object to be recognized on a holographic plate processed with $\gamma = 1$, as has been shown by Chałasinska-Mucukow and Nikta [13]. In this optical way an accurate and continuous POF, $H^p_{\lambda_1}$ may be experimentally obtained.

Nevertheless, there could be some advantages in restricting $H^p_{\lambda_1}$ to a binary function, giving rise to binary phase only filters (BPOF) [15,16]. This is the case, for instance, in the computer generation of the POF or for real time applications dealing with spatial light modulators. Aside from the quantization errors, the results obtained with BPOF are comparable with those achieved with continuous POF.

3. Results

In this section, the results of the numerical simulation of the recognition procedure proposed in the previous section are presented. The recognition has been performed with two types of objects, both presenting separate zones red, yellow and green. When illuminated by different wavelengths, each zone has different transmittance values. For the sake of simplicity the objects were chosen with a very low transmission value for the short wavelengths of the visible spectrum. In this way, the exposition of results is shortened without loss of generality. Table 1 shows the transmittance values of each zone red, yellow and green of the objects when they are illuminated by the green $\lambda_1 = 514$ nm (Ar laser) and red $\lambda_2 = 633$ nm (HeNe laser) wavelengths.

Fig. 1a shows the scene corresponding to the first type of object. The object placed at the upper left corner of this figure is the pattern to be recognized. Fig. 1b and 1c show the transmittances of the scene when illuminated by the green and red wavelengths

Table 1
Transmittance of the colour sectors.

Sector	Transmittance	
	$\lambda_1 = 514$ nm	$\lambda_2 = 633$ nm
Red	0.1	0.8
Yellow	0.8	0.9
Green	0.7	0.2

respectively. These transmittances will be referred to as green and red components. In this figure, it may be seen that the four objects present variations of shape and colour. But when the scene is illuminated by the wavelength $\lambda_1 = 514$ nm, some ambiguity arises between the objects 1 and 3, whereas if $\lambda_2 = 633$ nm is used the ambiguity appears between the objects 1 and 2.

The scene corresponding to the second type of object is shown in fig. 2a. The green and the red components are shown in fig. 2b and 2c respectively. As may be seen, with these objects the shape remains unchanged and only the colour distribution is modified.

In the following, we shall first describe the results obtained for the objects of fig. 1. If the filter is matched to the green component of the object 1 and the same wavelength is used in the correlator, we obtain the results shown in fig. 3a. Table 2 gives the values of the four direct correlation peaks. As the information corresponding to the green component has only be used, it is observed an ambiguity in the detection between objects 1 and 3. This result was expected due to the similar amplitude transmittance of both objects (fig. 1b). When the filter is matched to the red component and the correlator works with this wavelength, the results are those shown in fig. 3b. Now the ambiguity arises between objects 1 and 2. The corresponding values of the direct correlation peaks are given in table 2. Moreover, this table also shows the values of the crossed correlation peaks. They are very small and, when using a multiplexed filter, can be separated from the direct correlations as was pointed out above.

Thus, the object 1 cannot be recognized when the information provided by only one channel is used. On the contrary, the utilization of the information of

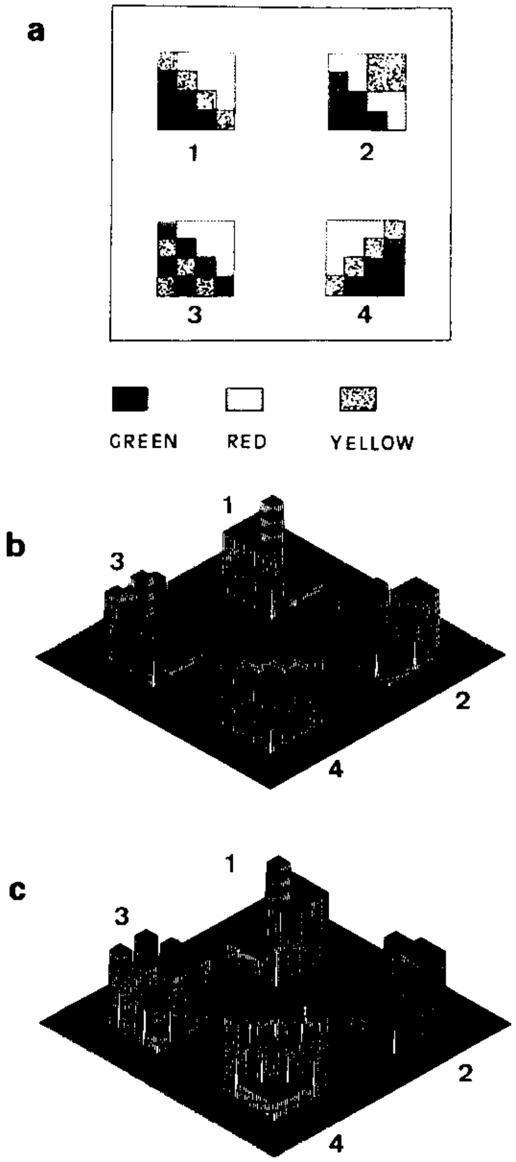

Fig. 1. Scene corresponding to the first type of object. Objects with shape and colour variations. The object to be recognized is number 1. (a) Colour distribution. (b) Green component. (c) Red component.

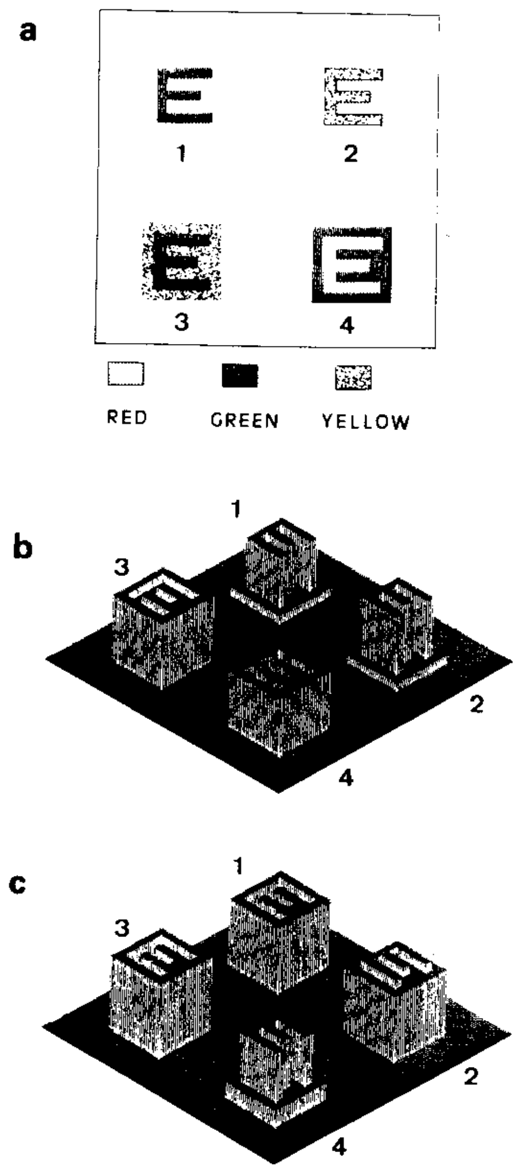

Fig. 2. Scene corresponding to the second type of object. Objects with only colour variations. The object to be recognized is number 1. (a) Colour distribution. (b) Green component. (c) Red component.

both channels green and red allows its recognition without any ambiguity.

We apply a threshold of 0.6 of the maximum correlation peak in both green and red channels. Thus, the cross-correlation signals corresponding to the objects 2 and 4 in the green channel and the objects 3 and 4 in the red channel are discarded. Therefore, object 1 is the sole object presenting a correlation peak in both channels simultaneously and, as a consequence, it is recognized without ambiguity.

The POF increase the discrimination between similar objects. Therefore, we have also introduced

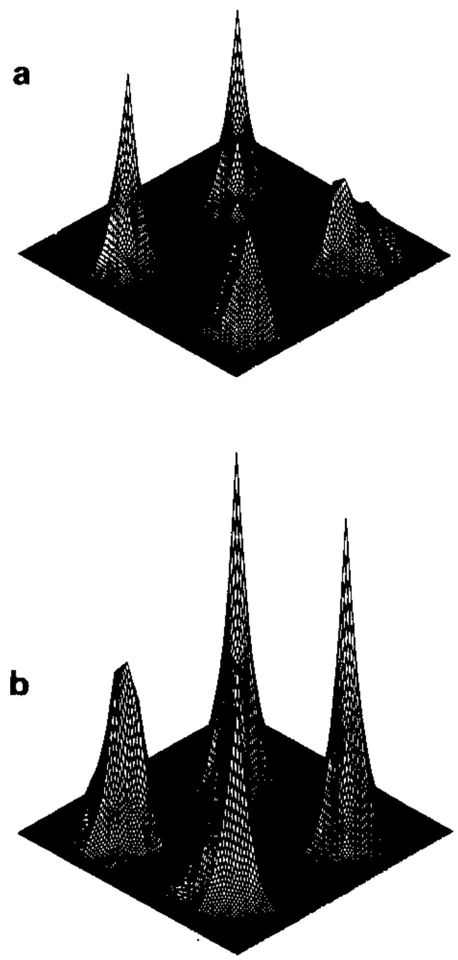

Fig. 3. Intensity of the correlation with CMF for the first type of object. (a) Green-green correlation. (b) Red-red correlation.

these filters in order to improve the performance of our recognition procedure. Fig. 4 and table 3 show the correlation signals and the values of the correlation peaks for both channels when continuous POF are used. Now, the correlation peaks become narrower and the value of the correlation intensity is higher than with the classical matched filters due to the increased efficiency of the POF. The ambiguity between the objects 1 and 3 in the green channel and between the objects 1 and 2 in the red channel does not disappear. However, the values of the peaks corresponding to the other objects are now smaller and to discard them a threshold of 0.3 of the maximum value is necessary. The method to recognize the pattern we are seeking is the same as in the case of CMF but with more relaxed conditions.

Table 2
Values of the correlation peaks when the filter is matched to the transmittance for the wavelength given in the first column (Fil) and the correlator is illuminated by the wavelength given in the second column (Cor). CMF are used. First type of object. $\lambda_1=514$ nm, $\lambda_2=633$ nm.

Fil	Cor	Intensity correlation values			
		Ob.1	Ob.2	Ob.3	Ob.4
λ_1	λ_1	4.5	1.9	4.5	2.4
λ_2	λ_2	7.9	7.8	4.2	4.6
λ_1	λ_2	0.5	0.6	0.6	0.6
λ_2	λ_1	0.8	1.0	0.8	1.1

As mentioned above, the second type of objects we used present only colour variations and the geometrical shape is the same. As in the previous scene, the pattern to be recognized is located at the upper left corner of the scene (fig. 2).

The correlation intensity and the values of the correlation peaks, when CMF are used for each channel, are shown in fig. 5 and table 4 respectively. As may be seen, the heights of the correlation peaks for the objects 1, 2, and 3 are similar and even slightly greater for the objects 2 and 3 than for object 1. This may be attributed to the fact that objects 2 and 3 differ from object 1 in the yellow zones. The transmittance of these yellow regions is greater than the corresponding red and green ones in the pattern to be recognized. Thus, due to these facts, it is impossible to discriminate between object 1 and objects 2 and 3 when the CMF is used, even when using the information provided by both the green and the red channels.

The correlation intensity and the values of the correlation peaks when POF are used for each channel are shown in fig. 6 and table 5 respectively. In this case, only two important peaks appear for each channel. For the green one, the ambiguity arises between objects 1 and 3; for the red one, between 1 and 3. With a similar procedure to the one employed with the first type of object, we shall be able to recognize the desired pattern. For each channel, a threshold is performed, neglecting the signals remaining under half of the maximum correlation peak value. The existence of a common peak for both channels pro-

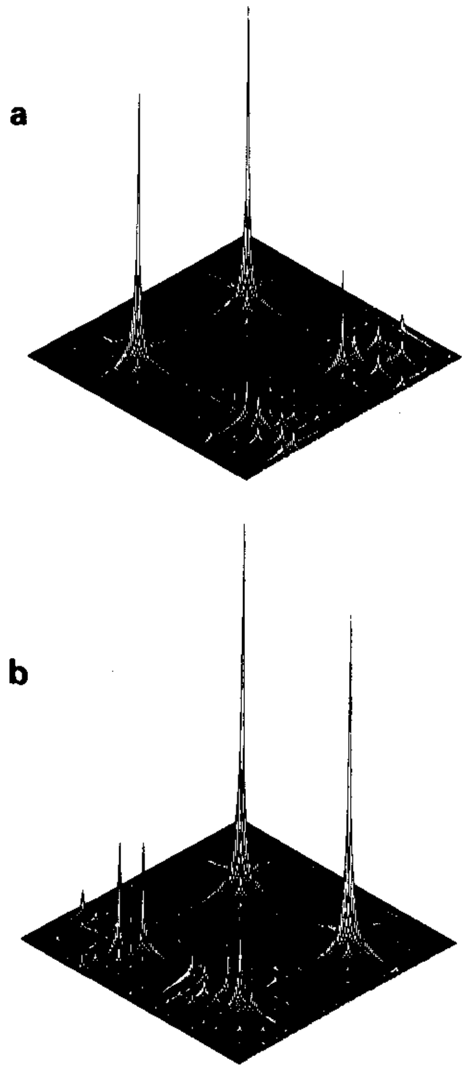

Fig. 4. Intensity of the correlation with POF for the first type of object. (a) Green-green correlation. (b) Red-red correlation.

vides, without ambiguity, evidence of the presence of the desired signal in the scene.

Therefore, for these objects with different colours but with the same shape, we show that only the use of POF provides the recognition. This is because the latter filters are more sensitive to the relative intensity changes between different parts of the object (edges) than the CMF. So, objects 1 and 2 present similar intensity changes for the green component whereas objects 1 and 3 present an analogous behaviour for the red component. These characteristics agree with the results obtained in the computer simulation of the correlation process.

The importance of the relative intensity changes can also be seen in the red channel for object 2 (fig. 6b) The intensity change between the square and

Table 3
Same as in table 2 using POF.

Fil	Cor	Intensity correlation values			
		Ob.1	Ob.2	Ob.3	Ob.4
λ_1	λ_1	19	5.4	17	3.3
λ_2	λ_2	23	22	6	5.9
λ_1	λ_2	0.29	0.27	0.44	0.46
λ_2	λ_1	0.75	0.74	0.58	0.89

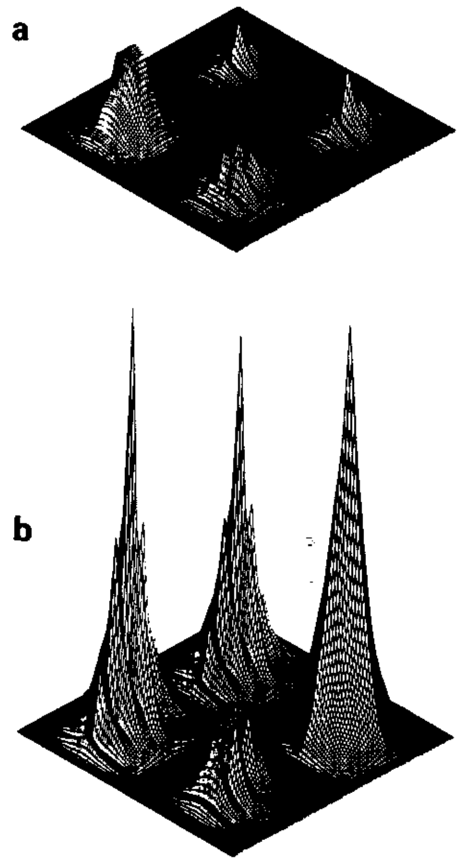

Fig. 5. Intensity of the correlation with CMF for the second type of object. (a) Green-green correlation. (b) Red-red correlation.

Table 4
Same as in table 2 for the second type of object.

Fil	Cor	Intensity correlation values			
		Ob.1	Ob.2	Ob.3	Ob.4
λ_1	λ_1	1.0	1.3	1.8	0.89
λ_2	λ_2	7.4	9.6	9.3	1.9
λ_1	λ_2	0.32	0.45	0.31	0.23
λ_2	λ_1	0.55	0.54	1.5	0.84

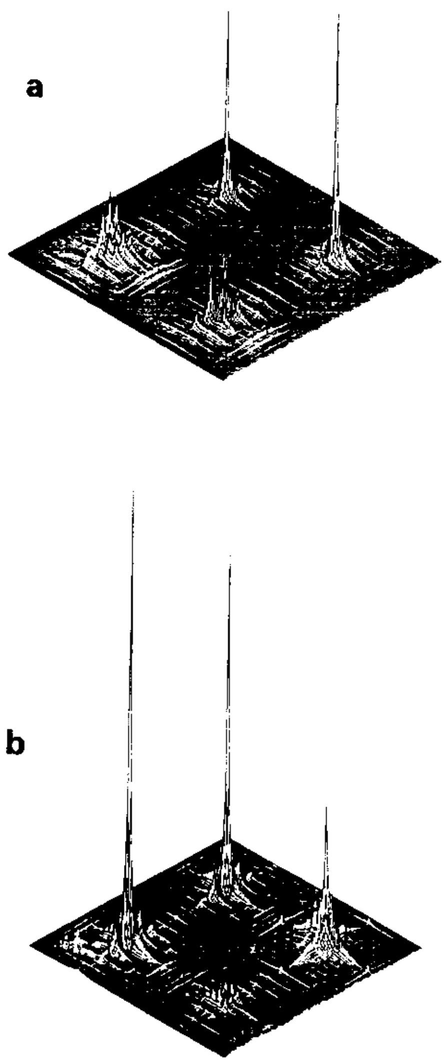

Fig. 6. Intensity of the correlation with POF for the second type of object. (a) Green-green correlation. (b) Red-red correlation.

Table 5
Same as in table 2 using POF and for the second type of object.

Fil	Cor	Intensity correlation values			
		Ob.1	Ob.2	Ob.3	Ob.4
λ_1	λ_1	14	18	4.5	4.1
λ_2	λ_2	28	12	37	1.8
λ_1	λ_2	0.73	0.87	0.81	0.73
λ_2	λ_1	0.36	0.40	0.93	0.90

the black background accounts for the existence of a smaller correlation peak for object 2.

4. Conclusions

We propose a technique for the recognition of colour objects. This is based on the study of successive correlations with filters matched to the object transmittance for different wavelengths. The coincidence of the correlation peaks in the different wavelength channels allows the identification of the test.

The method has been applied to two different types of objects: Objects with shape and colour variations and objects with only colour variation. CMF and POF have been used. The discrimination capability of both filters is studied with the two types of objects.

Objects with shape and colour variation can be identified by CMF. The POF relaxes the correlation detection. For objects with the same shape and colour variation, the CMFs present ambiguities which do not permit the identification even when using the information in several channels.

We have shown that the use of POF permits the identification of the second type of objects by using the information in different wavelength channels. This is due to the higher capability of these filters to discriminate between similar objects.

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Experimental results in color pattern recognition by multichannel matched filtering

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Abstract. The feasibility of polychromatic object recognition by multichannel correlation is experimentally demonstrated. Objects whose shape changes with the wavelength of the illumination beam are used. Separate high-pass matched filters, each one recorded with a different wavelength, are successively employed to perform the recognition of a polychromatic signal without ambiguity. Results of numerical simulation are also presented.

Subject terms: polychromatic pattern recognition.

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1 Introduction

In the last few years, there has been a growing interest in exploiting the color content of objects in pattern recognition processes. Conventional image recognition takes into account only the monochromatic information of the objects. As in human perception, color information should further increase discrimination sensitivity.

Matched filtering is a powerful technique in pattern recognition because the desired object can be identified in a scene without scanning. Since the VanderLugt matched filter was introduced,[1] there has been great progress in the generation of spatial filters, both optical and digital, for diverse applications in pattern recognition (see, e.g., Ref. 2). In the area of traditional matched spatial filtering and coherent optical correlation, Case[3] developed a wavelength-multiplexed filter to provide pseudo color-coded responses that allow the simultaneous recognition of several achromatic objects. This paper[3] discusses the secondary cross-correlation signals that appear when the illuminating wavelength of the correlator does not coincide with the wavelength used in the generation of the matched filter.

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Several optical, digital, and hybrid correlation methods have been proposed to recognize color images. In digital recognition, Badiqué et al.[4,5] developed a formulation to correlate color images. A projection of the polychromatic images on a color plane is performed before the digital correlation. The sharpness of the correlation peak can be optimized by introducing a generalized color plane for the projection.

In hybrid recognition, matched filters are digitally generated and placed in an optical correlator. In this field, Gu et al.[6] deal with experimental optical implementation of statistical algorithms for recognition of color patterns. In the design of the spectral-spatial filter, the calculated discriminant functions are used to synthesize the filter in a holographic spatial filter recording setup. The statistical pattern recognition is carried out using incoherent optical correlators.

In optical recognition, Yu[7] used a coherent optical correlator illuminated by three collinear laser sources of different colors. A grating placed in the input plane encodes frequency distribution for the three colors, and it is used in filter synthesis and in color image correlation. The correlator operates in parallel for the three colors. The filter can be a spectral-spatial filter matched to different color objects, providing their simultaneous recognition. Broadband illumination,[8] phase-only filters,[9] and spatial light modulators[10,11] have been used to achieve noise reduction, to increase discrimination abilities, and to perform real-time optical color recognition, respectively.

In color pattern recognition, further studies taking into account the spatial distribution of color as the main feature to distinguish between polychromatic objects would be interesting. In two previous papers,[12,13] we proposed a multichannel correlation process to recognize a polychromatic object by means of its identification in several monochromatic channels. Sometimes, the object can be distinguished only on the basis of color information, and the multichannel decomposition permits its incorporation in the recognition process. Performances of classical matched filters (CMF) and phase-only filters (POF) were numerically simulated for different types of objects. For objects consisting of a color alphanumeric character on a background of different color, we have proposed two strategies to recognize the whole object, with a given shape and color combination, or to recognize the shape regardless of its color combination.[14]

Some procedures for the optical synthesis of matched spatial filters that improve light efficiency and discrimination sensitivity have been proposed for monochromatic pattern recognition.[15–17]

This paper presents the optical implementation of the multichannel recognition procedure for polychromatic objects by means of optical synthesis of improved CMF for each wavelength channel. We are interested in the experimental response of the system when the scene to be analyzed presents some critical conditions. We consider objects with different spatial chromatic distributions but with similar amplitude distribution under the monochromatic illumination of some given channels. Such objects can be easily distinguished by the human eye but can produce false alarms when using a conventional monochannel correlator. Some other papers on color pattern recognition also study the feasibility of the recognition process but often deal with objects presenting a different shape and a rather uniform color distribution. They also do not explore the selectivity of the system in terms of the color content of the objects. In this sense, we present experimental results obtained with model objects that allow us to better check the multichannel correlator response than most of real life scenes. The results obtained using high-pass matched filters and bleached filters are discussed and compared.

2 Multichannel Correlation

The idea of pattern recognition in different monochromatic channels is based on the strong dependence of both the shape and the intensity distribution of a polychromatic object on the illuminating wavelength.

To detect the polychromatic signal, three separate matched filters should be recorded using three different wavelengths that cover the visible spectrum. It is also possible to record the same information on a multiplexed matched filter.[12] Then, the filters are placed in a classical achromatic optical correlator working with the three previous wavelengths.

Each filter is matched to the amplitude distribution $O_\lambda(x_1,y_1)$ of a signal under a given monochromatic illumination λ, where (x_1,y_1) are the coordinates on the object plane of the correlator. In the following, we refer to this amplitude distribution as the color component of the object.

Let us suppose that we want to recognize the colored object $O(x_1,y_1)$ contained in the scene $G(x_1,y_1)$, which is also polychromatic. When illuminated with a given wavelength λ, the color component of the scene can be represented by

$$G_\lambda(x_1,y_1)=O_\lambda(x_1-x_1', y_1-y_1')+N_\lambda(x_1,y_1) , \quad (1)$$

where (x_1',y_1') are the coordinates of the point where the object is centered and $N_\lambda(x_1,y_1)$ represents the color component of the rest of the scene.

To obtain the matched filter, we record, as usual, a Fourier transform hologram of the color component $O_\lambda(x_1,y_1)$ of the object. If the reference beam impinges on the plate at an angle θ and f is the focal length of the transforming lens, then the filter function can be written as

$$\tilde{H}_\lambda(x_2/\lambda f, y_2/\lambda f)=\exp(-jkx_2 \sin\theta)\tilde{O}_\lambda^*(x_2/\lambda f, y_2/\lambda f) , \quad (2)$$

where (x_2,y_2) are the coordinates on the Fourier plane of the correlator. In this plane, we have the product of this filter function [Eq. (2)] by the Fourier transform of the scene, $\tilde{G}_\lambda(x_2/\lambda f, y_2/\lambda f)$.

In the correlation plane (x_3,y_3), the autocorrelation,

$$O_\lambda(x_3,y_3)\otimes O_\lambda(x_3,y_3) , \quad (3)$$

is detected, centered at the point

$$x_3=-f\sin\theta+x_1' \qquad y_3=y_1' . \quad (4)$$

This well-known result for monochromatic correlators does not necessarily mean that the polychromatic scene contains the color object but only its component for the wavelength used in the process. Every object in the scene showing a similar color component as $O_\lambda(x_1,y_1)$ will be detected in the λ-illuminated correlator channel. Equation (4) shows that the autocorrelation peak position is independent of the wavelength. Only the object $O(x_1,y_1)$ will give successive maxima at the point given by Eq. (4), in the three successive λ channels. If these three successive maxima do not appear, then the polychromatic object sought is not contained in the scene. For different channels, the number of maxima in the same point reveals the number of color components similar to those in the target. These results provide information about the degree of similarity of the color content of the objects in the scene.

The requirements of filter-positioning devices can be reduced by using a multiplexed filter matched to the three color components of the objects. If a multiplexed filter is matched to the three color components of the object, the three subsequent correlation distributions (direct correlations) appear superimposed on the output plane. Moreover, cross-correlations are obtained when the illuminating wavelengths are different from that used in the synthesis of the filter. They are usually of low intensity and do not disturb the recognition process. Nevertheless, it is convenient to separate them from the direct correlations. This can be achieved by a proper choice of the parameters of the correlator.[12] If a multiplexed filter is used, the correlation responses of each channel must be registered separately by illuminating the correlation with the three wavelengths successively or by inserting a selective color filter at the input of the detector. This must be done to analyze the objects

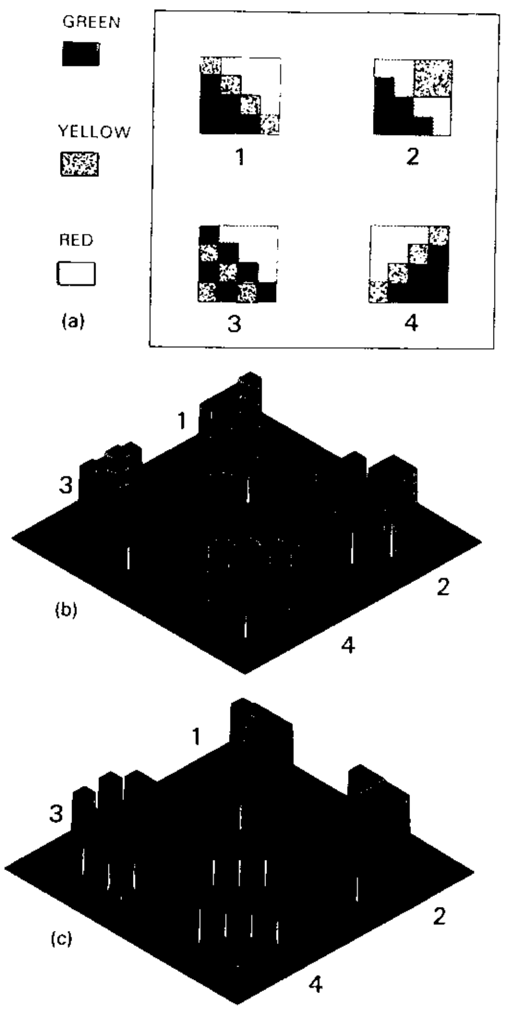

Fig. 1 Polychromatic scene: (a) color distribution, (b) green component, and (c) red component. The object to be recognized is number 1.

that produce a correlation maximum in all channels (objects to be identified as the target) or in only some of them (objects to be discarded).

3 Experimental Setup and Results

In the optical experiment, we deal with model objects composed of red, yellow, and green zones, like those in the scene shown in Fig. 1(a). For objects showing such colors, blue components can be considered negligible so that the number of channels necessary for recognition is reduced to two (green and red). Every object was limited by a 4-mm-side square aperture. The scene was composed of four such objects with a separation of 8 mm between their centers. In Fig. 1, the object to be recognized is placed at the upper left corner of the scene (object 1).

The objects are made using gelatine color filters, juxtaposing the different color zones. With these objects, we try to optically simulate color pattern recognition using color slides, but with more selective spectral transmittances. We have selected three color gelatine filters whose transmission

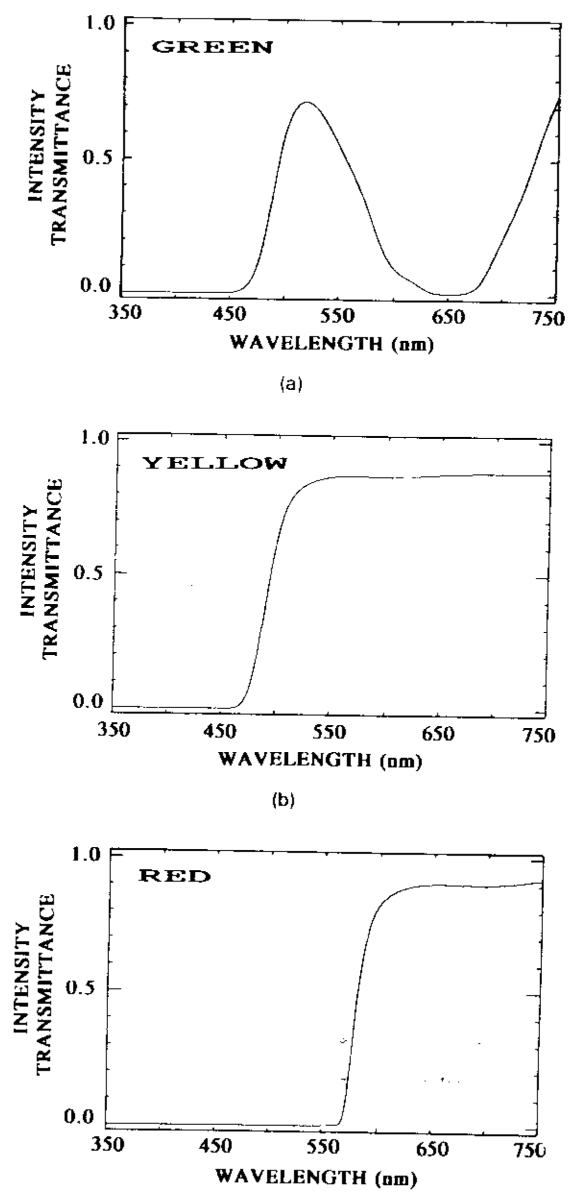

Fig. 2 Intensity transmittances of Kodak Wratten filters used for the generation of the model objects: (a) green, (b) yellow, and (c) red.

curves are given in Fig. 2. The amplitude transmittance values of the selected color filters for green ($\lambda_1 = 514$ nm) and red ($\lambda_2 = 633$ nm) wavelengths are given in Table 1. The color gelatine filters chosen provide a good definition of the color components of the objects. The red filter presents a high transmittance for the red wavelength and a very low transmittance for the green wavelength, and vice versa for the green filter. The yellow filter presents almost the same transmittance for the red and green wavelength. With this scene, we ensure the critical conditions under which we had planned to test the multichannel correlation process. As we can see from the green and the red components of the scene [Figs. 1(b) and 1(c), respectively], objects 1 and 3 have similar green components and objects 1 and 2 have

Table 1 Amplitude transmittance values of the color gelatine filters used in the generation of the model objects for the wavelengths of the lasers used in the experimental setup.

Kodak Wratten	Colour	Amplitude transmittance	
		$\lambda 1$=514 nm	$\lambda 2$=633 nm
23A	Red	0.00	0.95
8	Yellow	0.89	0.93
59	Green	0.84	0.10

similar red components. Although the human visual perception clearly distinguishes objects 1, 2, and 3 by their spatial color distribution, an optical correlator working under the illumination of only one of the λ_1 or λ_2 wavelengths would not.

This experiment with idealized objects might be considered an optical simulation of some special cases of real color recognition problems. Depending on the particular problem, either a color slide or spatial light modulators could be used for coherent optical correlation. A color slide has some interesting advantages, such as the reproduction of the color information, good resolution, and low cost. On the other hand, it represents a severe restriction in a real-time recognition process that operates directly with diffusely reflecting objects. For such processes, the use of spatial light modulators can be the solution, but because they are monochrome, the red-green-blue (RGB) decomposition must be done before performing the correlation. The color components could be recognized successively in an optical correlator, which would need only one wavelength for the illumination.

3.1 *Numerical Results*

In previous papers[12,13] we presented a numerical simulation of the method. We showed the corresponding correlations obtained with classical matched filters (CMFs) and phase-only filters (POFs) for the red and green channels. In this section, we present numerical results obtained with the amplitude transmittance values given in Table 1. Figures 3 and 4 show the results obtained in the correlation plane for each channel with CMFs and POFs, respectively. With both kinds of filters, objects 1 and 3 are detected in the green channel, as can be seen in Figs. 3(a) and 4(a), and objects 1 and 2 in the red channel, as shown in Figs. 3(b) and 4(b). Taking into account the information provided by both λ channels, object 1 is identified without ambiguity as the signal to be detected. Although objects 2 and 3 present different color distributions than object 1, they have one color component that is similar to the corresponding component of object 1. When working with one channel, detection ambiguities can be expected for objects of this kind. The use of a POF allows us to take a lower threshold value than in the case of a CMF, and so the detection conditions are more relaxed.

3.2 *Optical Setups*

The correlator used to perform the optical experiment was composed of two Fourier transformers (FTs) in cascade working under spherical beam illumination, as shown in Fig. 5. The lenses used in the system were achromatic doublets to avoid as much as possible the effects produced by wavelength variations. To synthesize the matched filters, we used the holographic device of Fig. 5, composed of the Fourier transformer FT_1 and the reference beam. To obtain matched filters, two plates were recorded, each of them with a different wavelength. We assume, as is usual, that we are working in the linear region of the T-E curve. After development, we obtain two separate filters matched to the green and red components of the object to be detected. This setup is also useful for the generation of multiplexed filters matched simultaneously to both color components of the object.

Once the reference beam is removed, the recognition of the signal is performed in the optical correlator of Fig. 5 composed of the Fourier transformers FT_1 and FT_2. The correlation intensity distribution is scanned by a CCD line detector placed at the output plane of the correlator and coupled to an oscilloscope.

As matched filters, we use both classical matched filters and bleached filters, which are obtained by over-exposing the spectral information of the signal when recording the hologram. In this way, we obtain high-frequency-enhanced filtering, providing sharper correlation signals.[15] The filters are made on Agfa Holotest 8E56 plates for the green channel and Agfa Holotest 8E75 plates for the red channel.

3.3 *Experimental Results*

In the first experiment, we tested the possibilities of our method by considering recognition when the scene contains only the object to be detected. We performed the recognition with both types of matched filters. For instance, Fig. 6 shows the autocorrelation signals in the red channel obtained using a CMF [Fig. 6(a)] and a bleached filter [Fig. 6(b)]. In both cases, we detected the corresponding peak correlation. As can be seen, the signals saturated the CCD detector. We did not reduce the response to show the background and the level of noise in each case. With bleached filters, we obtained a higher intensity peak but also an increase in noise. In our case, the use of bleached filters did not improve the response of the system. Therefore, in the following experiment, we present only the signals obtained when a CMF is employed. To avoid the saturation of the detector, neutral filters are placed in front of the CCD line.

The second experiment consists of the detection of object 1 in the scene of Fig. 1(a). To identify this object, the direct correlations are obtained by successively placing the filters matched to the color object components and by illuminating the correlator with the same wavelength that we used in the filter recording. Figures 7(a) through 7(d) show the direct correlations, in the green channel, of each object of the scene with object 1. In a similar way, Figs. 7(e) through 7(h) show the direct correlations corresponding to the red channel.

As we expected from numerical simulation results, an ambiguity arose in the green channel, between objects 1 and 3, and in the red channel, between objects 1 and 2. The information provided by the two channels permits the identification of object 1 without ambiguity. The object is detected by applying the AND operation to the correlation peaks of both channels.

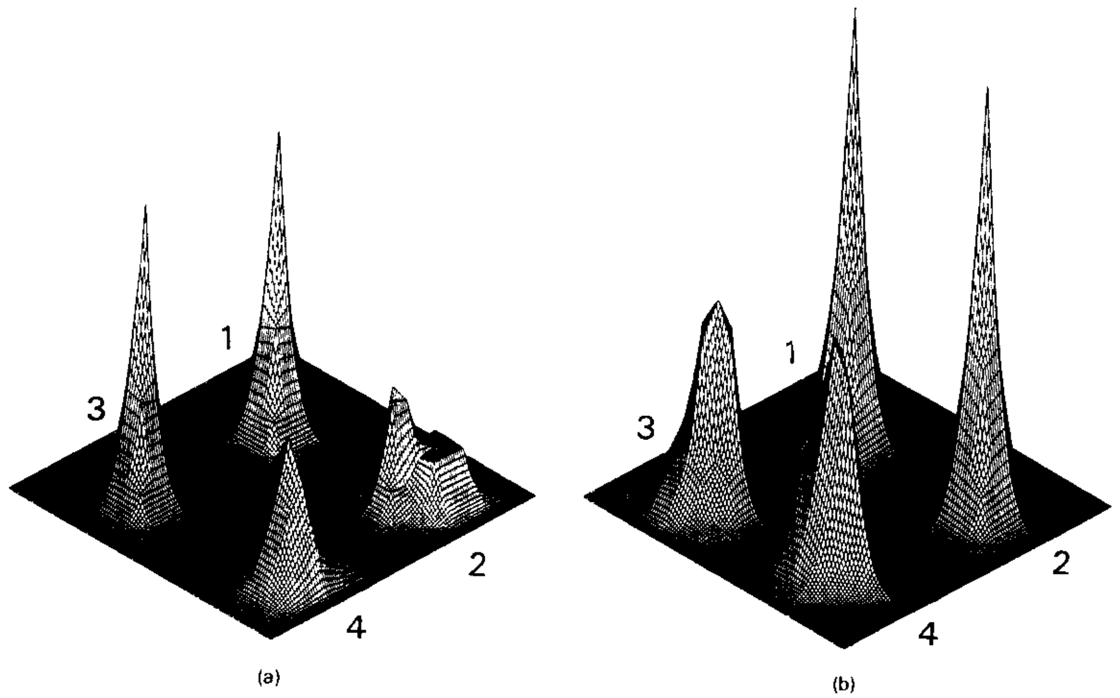

Fig. 3 Intensity of the correlation with a CMF between the scene and the object to be recognized obtained by numerical simulation: (a) green channel and (b) red channel.

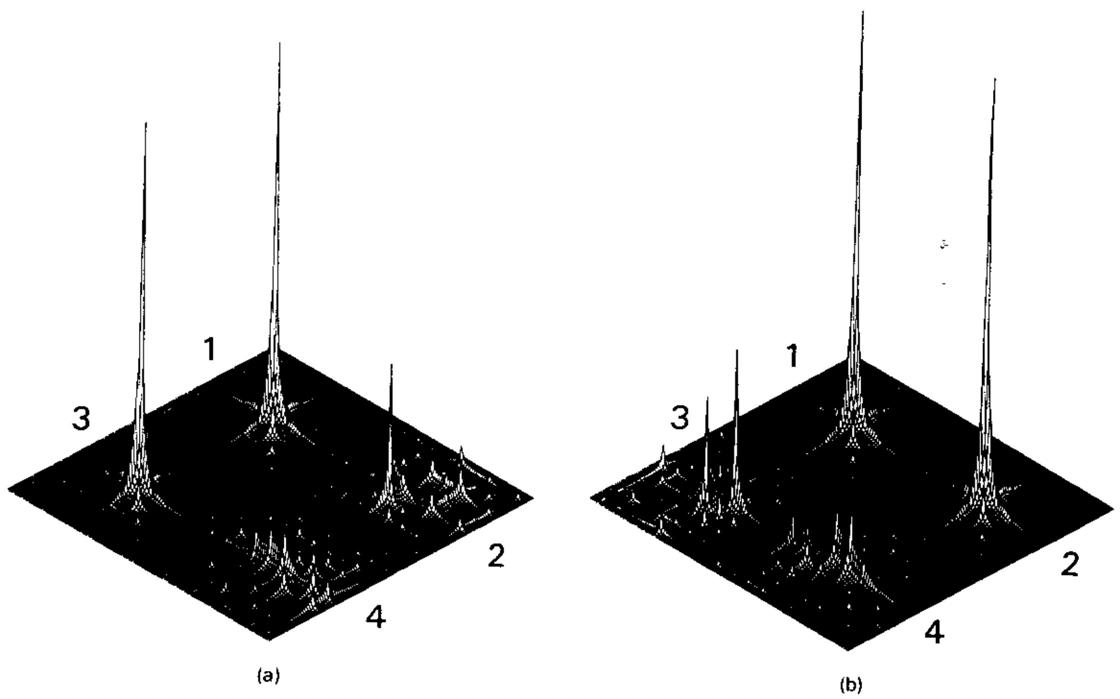

Fig. 4 Intensity of the correlation with a POF between the scene and the object to be recognized obtained by numerical simulation: (a) green channel and (b) red channel.

Finally, we completed this experiment by obtaining the cross-correlations in each channel to determine their magnitude and the ability of the system to separate them from the direct correlations without overlap, which is important when using multiplexed matched filters. Figures 8(a) through 8(d) show these correlations for the green channel when the filter matched to the red component is used, whereas Figs. 8(e) through 8(h) show the corresponding cross-correlations for the red channel. In all cases, they are much lower than the respective direct correlations. In our case, the parameters

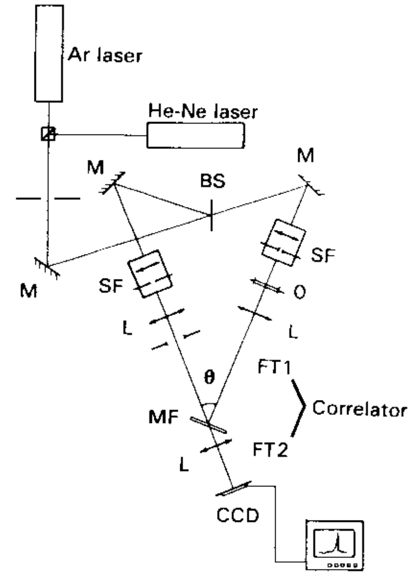

Fig. 5 Simultaneous representation of the experimental setups. The holographic device composed of the Fourier transformer FT_1 and the reference beam is used to record the matched filters. The correlator used to detect the signals is composed of both Fourier transformers FT_1 and FT_2.

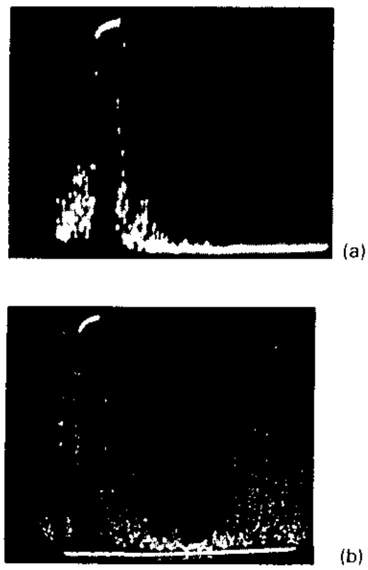

Fig. 6 Experimental autocorrelation of object 1 of Fig. 1(a) in the red channel with (a) a CMF and (b) a bleached filter.

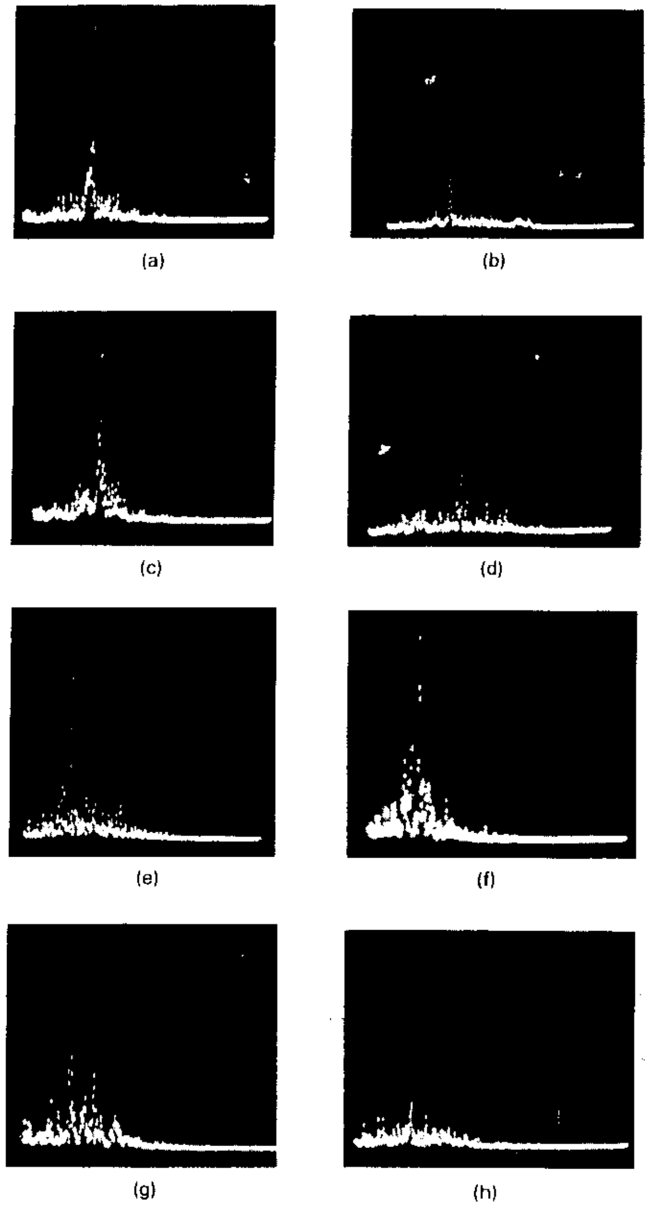

Fig. 7 Experimental direct correlations between the scene and the pattern to be recognized: (a) to (d) show the results for the green channel and (e) to (h) show the results for the red channel.

of the correlator and the size of the objects would allow the spatial separation of the cross and the direct correlations without any overlap.

4 Summary

Experiments in the pattern recognition of polychromatic objects were carried out to confirm the feasibility of the multichannel correlation method. An optical setup with two lasers was used to synthesize the filters and to perform the multichannel correlation. We studied the capability of the system to discriminate between model objects, which show adverse conditions to be distinguished without ambiguity under monochromatic illumination. To simplify detection, we considered objects with low transmittance in the blue region of the visible spectrum. Thus, the correlator works with two (green and red) channels only. The filters were matched separately to the color components of the object to be recognized. We considered the performance of high-pass CMF and bleached filters. Both kinds of filters provided identification of a given object. However, with the bleached filters, the level of noise and the correlation signal both increased. For this reason, we disregarded their use, bearing in mind that they do not improve the information obtained with the high-pass CMF.

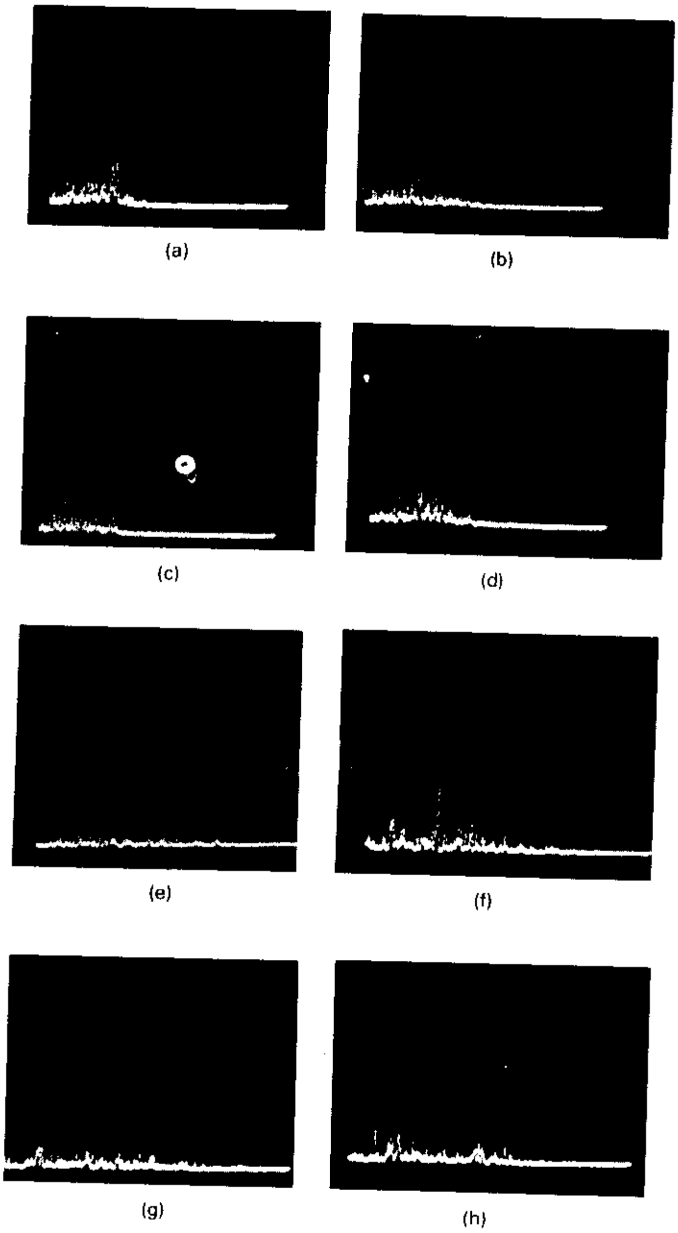

Fig. 8 Experimental cross-correlations between the scene and the pattern to be recognized: (a) to (d) show the results for the green channel when the filter matched to the red component is used and (e) to (h) show the results for the red channel when the filter matched to the green component is used.

The detection of a color object contained in a polychromatic scene has been experimentally performed with high-pass CMF. The identification was obtained from the successive direct correlations in the output plane. From the correlation peaks detected in both channels, the object was identified in the scene without false alarms.

In our experimental conditions, it is possible to use a multiplexed filter in the correlator to obtain direct and nonsignificant cross-correlations simultaneously without overlap.

Acknowledgments

We would like to thank H. Iturriaga and her research group for technical assistance in the measurement of the spectral transmission of the gelatine filters. The authors acknowledge the financial support of DGICYT (Dirección General de Investigación Científica y Técnica, Ministerio de Educación y Ciencia (Project PB87-0779). One of the authors (M.S.M.) thanks the CIRIT (Comissió Interdepartamental de Recerca i Innovació Tecnològica de la Generalitat de Catalunya) for partial financial help to develop this work during 1990.

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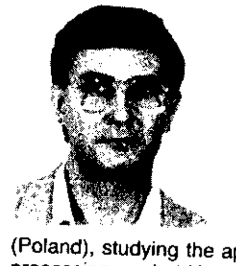

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Different strategies in optical recognition of polychromatic images

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We treat two different problems in the recognition of polychromatic images: (1) recognition of an object with a given shape and color combination; (2) recognition of an object regardless of its color combination. To solve each problem we propose different strategies. The number of filters and the objects to which the filters are matched vary with the strategy. Phase-only filters have been used to achieve recognition of both problems. Computer results are given for different targets and scenes to show the behavior of the proposed strategies.

Key words: Optical pattern recognition, color, phase-only filters.

I. Introduction

Coherent optical pattern recognition based on the correlation technique generally uses only one wavelength for matched filter recording and in the correlator. For a color object it gives information about the shape and the transmission of the object for this wavelength. Other techniques that provide information not only about the shape but also about the color of the objects increase the discrimination capability of the method because there are real objects that differ only in their color distribution.

Warde *et al.*[1] proposed a spectral and spatially matched filtering method in real time. The use of white light in optical processing has been described by Yu,[2] and the principles of processing with partially coherent light are described in Ref. 3. In Ref. 4 Yu described a technique that applies to an optical coherent correlator illuminated by polychromatic light. Three collinear coherent sources (red, green, and blue) were used. A diffraction grating was placed on the transparency. In the Fourier plane the frequency distributions for each of the three colors appear separately.

The use of a magneto-optic spatial light modulator permits the implementation of the above techniques in real time.[5] The system uses a multichannel spectrally matched spatial filter in a binary coherent optical correlator. Input color images are transformed into coherent binary color-coded images by a color grating.

The statistical recognition of images consists of the identification and classification of the objects. Gu *et al.*[6] presented a filter design with information about the shape and color for statistical recognition of color images. In the filter generation they consider a transform that extracts the feature of a class and passes from observation space to decision space with minimum error. The correlator uses incoherent illumination, and the color information is decomposed into three channels, red, green, and blue. The results show that the classification power of the algorithm increases when the filter contains information on shape and color instead of information on shape only.

Badiqué *et al.* have proposed a formulation for digital color image correlation.[7–9] A three-dimensional vector color image is transformed into a two-dimensional vector image by projection onto a color plane. In Refs. 8 and 9 they found an optimum generalized color plane to carry out the correlation operation. With this formulation they obtained a spatial–spectral recognition filter with more discrimination capability than the filter obtained from the intensity distribution. In Ref. 10 they proposed a complex synthetic discriminant filter to obtain rotation-invariant and scale-invariant recognition.

In two previous papers[11,12] we proposed a method based on multichannel correlation to recognize polychromatic objects according to the shape and the color

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information of the target. We pointed out some cases for which the use of classical matched filters (CMF's) does not provide enough discrimination capability whereas the use of phase-only filters (POF's) does.

In this paper we deal with other situations and problems related to the recognition of polychromatic objects that consist of an alphanumeric character on a square of a different color. Two problems are considered: (1) recognition of an object with a given character and a given color combination; (2) recognition of the character regardless of its color combination. To solve these problems, two different strategies must be followed.

In the first part of this paper we study problem (1). The strategy that follows is the same as that proposed in Refs. 11 and 12, i.e., the filter used in each channel is matched to the object transmittance for the illuminating wavelength of the channel. To complete the results of the previous papers, we check the POF performance in some adverse conditions such as those created by a small character–background contrast in some channels or by a character area that is much smaller than the square background area.

In the second part of this paper we study problem (2) for which a different strategy is proposed. Filters matched separately to the two sectors of the object are used in each channel. With these filters, we obtain enough information for recognition of the character shape.

These techniques for polychromatic recognition are especially useful when we record the intensity variations of the target and the scene, both being color images, that provide images with low contrast. So this problem can also occur when a single wavelength is used to perform the correlation between polychromatic images. We give some practical examples of recognition processes for which the assumed combinations of spatial–spectral information of objects are relevant: the identification and classification of fruits depending on their shape and degree of ripeness; the identification of labels, anagrams, flags, traffic signals, etc.

II. Color Character Detection

In color pattern recognition, the multichannel recognition process is based on the fact that for a polychromatic object both shape and intensity distribution depend strongly on the illuminating wavelength. The recognition of the object in a scene is achieved by decomposing the information in three monochromatic channels and by identifying the object independently in each channel.

To perform the decomposition three wavelengths, λ_1, λ_2, and λ_3, that cover the visible spectrum are selected. The amplitude transmittances, $o_{\lambda i}(x_1, y_1)$ (with $i = 1, 2, 3$), obtained by successively illuminating the object with these wavelengths are called the color components of the object.

We use three channels to reduce the false alarms that can occur when a classical single-channel recognition process is used. These false alarms are produced when different polychromatic objects present a similar amplitude distribution under a given monochromatic illumination. In the multichannel process the identification of the target in all three channels considerably reduces the possibility of such false alarms.

Multichannel recognition is performed by using a 4f correlator (Fig. 1). To this end, filters matched to the signal $g_{\lambda i}$ are used in each channel. The kind of signal $g_{\lambda i}$ depends on the problem and on the strategy used. Following VanderLugt's holographic scheme, the CMF can be recorded. For each filter the term of its transmittance that provides the correlation may be written as

$$\exp(-i2\pi x_3 \sin\theta/\lambda i)G_{\lambda i}^*(x_3/\lambda_i f, y_3/\lambda_i f), \quad i = 1, 2, 3, \tag{1}$$

where $G_{\lambda i}$ is the Fourier transform of $g_{\lambda i}$, (x_3, y_3) are the Cartesian coordinates in the Fourier plane (Fig. 1), and f and θ are two parameters that correspond to the system used to record the filters, where f is the focal length of the transforming achromatic lens and θ is the angle between the normal to the holographic plate and the reference plane beam. For each channel the correlation between the scene and the object is obtained when the correlator is illuminated by the same wavelength that is used for recording the filter and is given by

$$o_{\lambda i}(x_c, y_c) * g_{\lambda i}(x_c, y_c), \quad i = 1, 2, 3 \tag{2}$$

for each wavelength, where (x_c, y_c) represent the Cartesian coordinates in the correlation plane. This correlation is centered at the point $x_c' = -f\sin\theta, y_c' = 0$. The position of the correlation does not depend on the wavelength. The object can be recognized by analyzing the information that is provided by all three channels.

Several features of the CMF and of the polychromatic objects cause false alarms in the recognition process. We examine the most important of these features in Section III. As is generally known[13,14] POF's are more sensitive to small differences between similar objects than CMF's. This property of the POF is based on its high-pass effect[13–15] that permits improvement of the discrimination capability of the recognition systems. Since the Fourier transform of a function is, in general, complex, $G_{\lambda i}$ can be

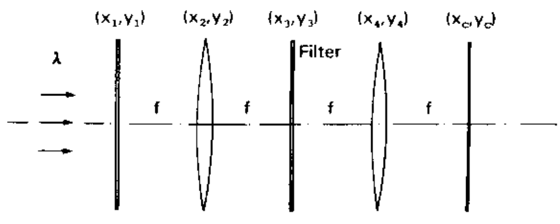

Fig. 1. Schematic representation of the 4f correlator.

represented as

$$G_{\lambda i}(x_3/\lambda_i f, y_3/\lambda_i f) = |G_{\lambda i}(x_3/\lambda_i f, y_3/\lambda_i f)| \times \exp[i\phi_{\lambda i}(x_3/\lambda_i f, y_3/\lambda_i f)]. \quad (3)$$

The CMF contains $G_{\lambda i}^*$. The POF $G_{\lambda i}^P$ is defined as

$$G_{\lambda i}^P(x_3/\lambda_i f, y_3/\lambda_i f) = \exp[-i\phi_{\lambda i}(x_3/\lambda_i f, y_3/\lambda_i f)] \quad (4)$$

and is obtained by setting the modulus $|G_{\lambda i}|$ in the CMF equal to unity.

We deal with objects that consist of a color alphanumeric character on a square background of a different color (see, for example, Fig. 2). This type of object represents a more general type of polychromatic image that maintains its shape even when the illuminating wavelength changes.

Our interest is focused mainly on two problems: (1) the recognition of an object as a whole, composed of a given character and a given character–background color combination; (2) the recognition of the character shape regardless of the character–background color combination of the object.

To solve the first problem the filters are matched to the color components of the object to be recognized as proposed in Refs. 11 and 12, where $g_{\lambda i} = o_{\lambda i}$. In this way the filters contain both shape and color information. The object is recognized when there is a coincidence of intensity maxima at the same point for all the channels; CMF's and POF's are used.

To solve the second problem we use two filters in each channel. One of the filters is matched to the character on a dark background $c(x_1, y_1)$, and the other is matched to a dark character on a bright background $b(x_1, y_1)$. With the signals $c(x_1, y_1)$ and $b(x_1, y_1)$ we seek to detect the character shape in the color components that present good contrast between the character sought and the background.

The transmittance of each object in the scene for a given wavelength λ_i may be represented by

$$o_{\lambda i}(x_1, y_1) = \alpha_i c(x_1, y_1) + \beta_i b(x_1, y_1), \quad (5)$$

where α_i and β_i are the amplitude transmittance factors of the character and the square background. Since the character and the background colors are different, the contrast between them is high in at least one channel. For this problem we use a POF because of the properties of these filters that make them more suitable for the detection of edges. If the character transmission is much higher than the background ($\alpha_i \gg \beta_i$) (direct contrast) we obtain a maximum in the correlation with the filter matched to $c(x_1, y_1)$. If the transmission of the background is much higher than the character transmission ($\beta_i \gg \alpha_i$) (inverse contrast) a maximum in the correlation with the filter matched to $b(x_1, y_1)$ appears. The presence of the character in the scene is detected by the existence of a maximum in any of these correlations.

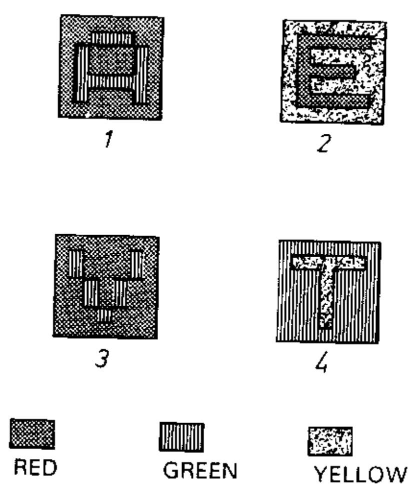

Fig. 2. Test 1.

III. Recognition of the Shape and the Color Combination

In Ref. 12 we have already given some previous results for the recognition of polychromatic objects according to the shape and the color content of the target. One object to be recognized was an alphanumeric character on a square of a different color. It was compared with objects that contain the same character and different color combinations. POF's were capable of discriminating the target whereas CMF's could not avoid the false alarms.

In this section we present the results obtained by computer simulation in order to complete our study about the recognition of a polychromatic object with a given character and a given character–background color combination. We check the CMF and POF performances when some circumstances make recognition difficult.

(1) Objects with low character–background contrast in some of their color components. This is due to the presence of a color that provides high transmittance in several channels (e.g., yellow).

(2) The area and therefore the energy of the character are much smaller than those of a square background. For example, we next consider as a target an object with the letter X, whose character–background area ratio is 1:4.4 (this ratio is 1:2 for the objects with the letter E considered in Ref. 12).

We examine these adverse conditions in two situations:

(A) the scene contains objects with different characters and diverse color combinations (test 1 in Fig. 2);

(B) the scene contains objects with the same character and all the possible combinations with the selected colors (test 2 in Fig. 3).

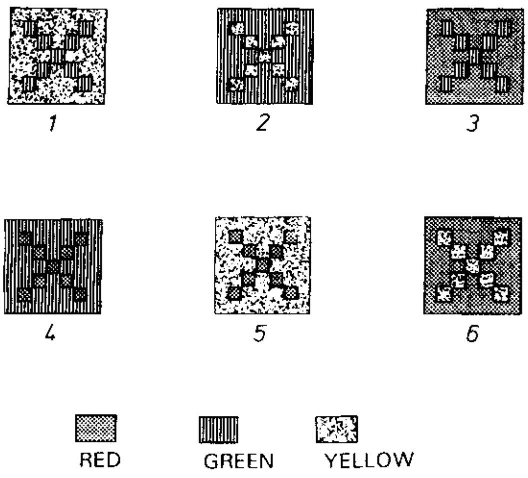

Fig. 3. Test 2.

The first scene is proposed to verify the capability of discrimination among characters. The second scene is considered to distinguish the character background as a whole. The polychromatic objects we have considered present separate zones of red, yellow, and green. They were chosen with a negligible amplitude transmission for the wavelengths that belong to the blue region of the visible spectrum. Thereby, only two channels are necessary to perform recognition, and the presentation of the results may be shortened without loss of generality. Table I shows the amplitude transmittance values of the red, yellow, and green zones when they are illuminated by the selected wavelengths, λ_1 = 514-nm (Ar-ion laser) for the green channel (GC) and λ_2 = 633-nm (He–Ne laser) for the red channel (RC). The color components of an object are the transmitted amplitude distributions of the object for each of these wavelengths.

As described in Section II, each color component of the target is recognized by using a filter matched to this component and by illuminating the correlator with a wavelength of the same color. Identification of the target is achieved after all its components have been recognized in the respective channels. This condition may be represented by the logical operator AND applied to the correlation results of the diverse channels.

For test 1 (Fig. 2), the object placed in the upper left-hand corner (object 1) is the target. To demonstrate the results obtained we first use CMF's. The correlations for the GC and the RC are represented by their intensity in Figs. 4(a) and 4(b), respectively.

Table I. Amplitude Transmittance of the Color Sectors

Sector	Amplitude Transmittance λ_1 = 514 nm	Amplitude Transmittance λ_2 = 633 nm
Red	0.1	0.8
Yellow	0.8	0.9
Green	0.7	0.2

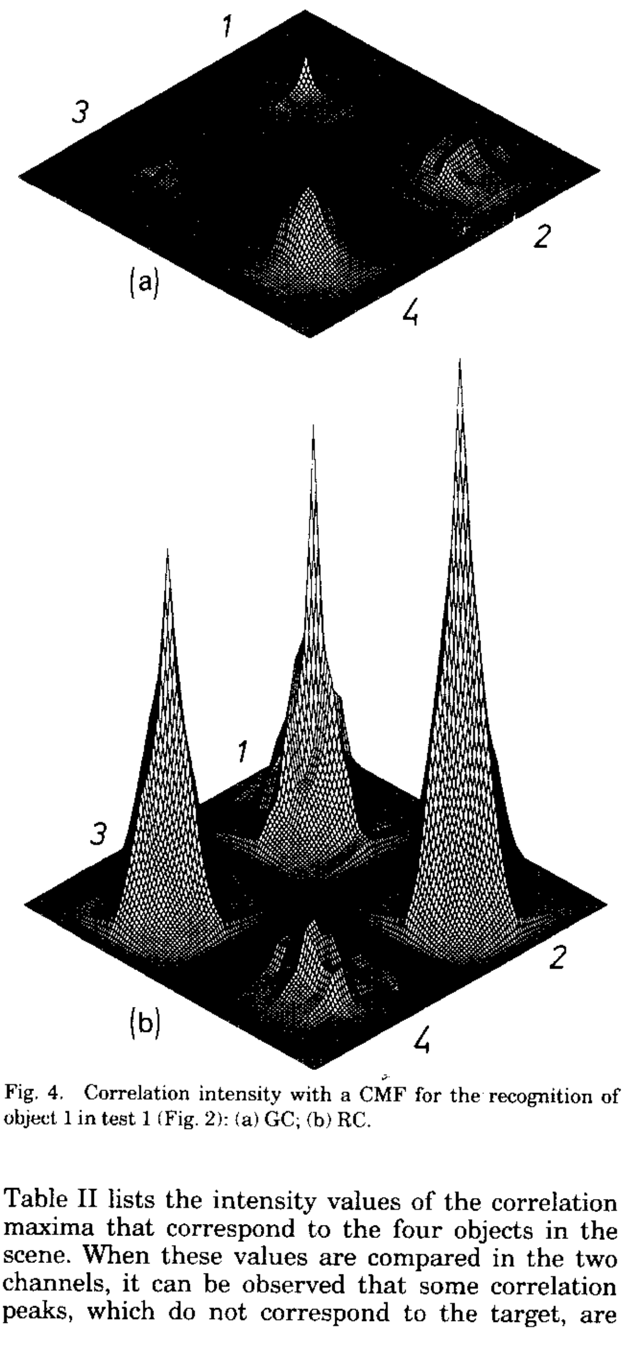

Fig. 4. Correlation intensity with a CMF for the recognition of object 1 in test 1 (Fig. 2): (a) GC; (b) RC.

Table II lists the intensity values of the correlation maxima that correspond to the four objects in the scene. When these values are compared in the two channels, it can be observed that some correlation peaks, which do not correspond to the target, are

Table II. Values of the Correlation Peaks Corresponding to Figs. 4 and 5

Filter	Channel	Intensity Correlation Values Object 1	Object 2	Object 3	Object 4
CMF	Green	**0.81**	0.74	0.25	**1.5**
CMF	Red	**8.2**	**11.3**	**7.4**	1.4
POF	Green	**18.4**	2.9	3.9	3.7
POF	Red	34.8	18.1	9.8	1.6

Peak values that exceed the threshold value (0.5 of the maximum value in each row) are boldfaced.

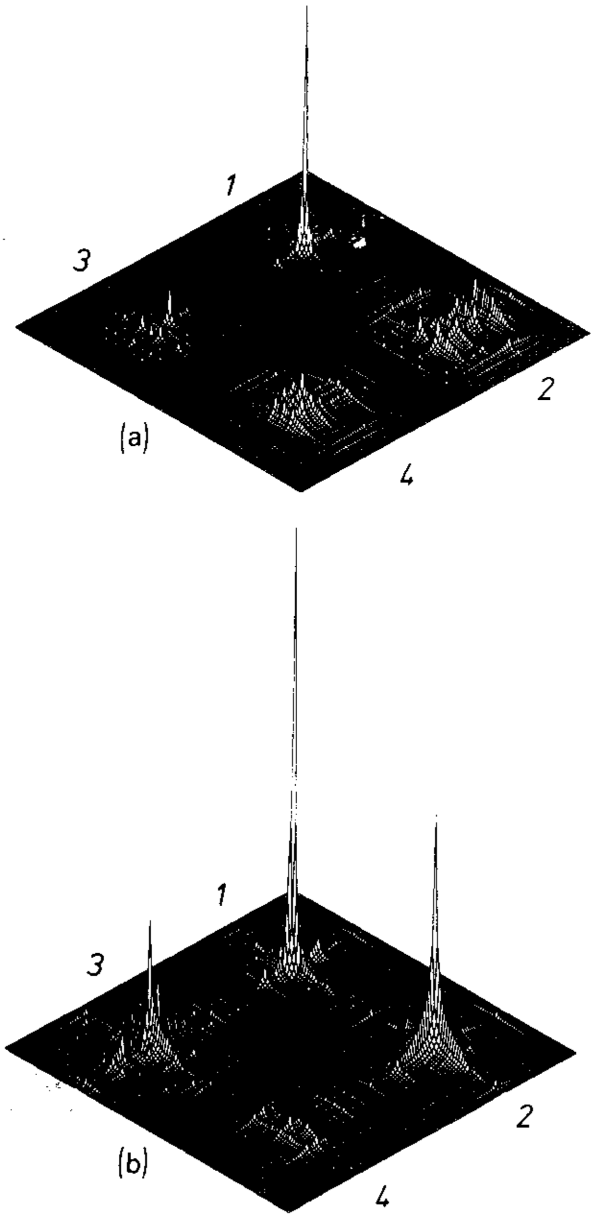

Fig. 5. Correlation intensity with a POF for the recognition of object 1 in test 1 (Fig. 2): (a) GC; (b) RC.

similar to or even higher than the autocorrelation peak. This is true of the correlations for objects 2 and 4 in the GC and for objects 2 and 3 in the RC. These results are accounted for because the objects that compose the scene have not normalized the energy of their color components, as might be expected in real polychromatic images.

In the GC the yellow background of object 2 shows high transmittance and provides an important cross correlation with the green letter A of the target. In the RC the red component of object 2 even contains the component of the target. Since the objects that obtain a correlation peak in both the GC and the RC are identified with the target, an ambiguity in the detection arises between objects 1 and 2. On the other hand, the great difference in shape between letters A and V gives rise to a low cross correlation in the GC, permitting us to discriminate between objects 1 and 3, despite having the same character–background color combination.

In Fig. 4 it is also observed that the correlation maxima in the RC reach much higher intensities than those in the GC. This is because in the RC the components of the target (object 1), objects 2 and 3, correspond basically to their square background, and the area of this sector (and consequently its energy) is at least twice as large as the area of the character in all the objects considered.

To increase the recognition capability of the system, POF's have been introduced. Figures 5(a) and 5(b) show the results obtained with these filters in the GC and the RC, respectively. Table II contains the values of the correlation peaks. When these results are compared with those obtained with a CMF (Figs. 4 and 5 and Table II), a substantial decrease in the correlation relative values of the objects distinct from the target is observed. This is due to the great sensitivity of the POF to the edges of the target, that is, to its high frequency content, whereas the information on the background, which belongs to low frequency content, is not enhanced by the POF. Thus, by using a POF, only object 1 attains the maximum value of the correlation intensity in both channels simultaneously and, therefore, it is recognized without ambiguity.

In test 2 (Fig. 3), objects with the same character and all the six possible character–background color combinations with red, yellow, and green are considered. Object 1 is the target. We chose this object because of the high transmittance of its square background under green and red illumination. This fact creates an additional problem for recognition because this high transmittance causes a low character–background contrast in one of the color components of the object (green), which is an adverse condition for the identification of the target.

When CMF's are used to recognize object 1 in test 2, some ambiguity arises between objects 1 and 5 even after the operator AND is applied. These results are not given in this paper in order to keep it short. Table III presents the correlation results when POF's are used. The peak value depends not only on the character shape but also on the square background. The correlation gives a peak if both the contrast at the

Table III. Values of the Correlation Peaks Obtained when a POF was used to Recognize Object 1 in Test 2 (Fig. 3)

	Intensity Correlation Values					
Channel	Object 1	Object 2	Object 3	Object 4	Object 5	Object 6
Green	**21**	13	2	**24**	**31**	2.8
Red	**50**	4.1	**38**	3.2	20	10

Peak values that exceed the threshold value in each row are boldfaced.

edge of the character and the contrast at the edge of the square are similar and in the same direction as the contrast in the target. To interpret these results we apply a threshold of 0.5 for the maximum correlation peak in each channel, GC and RC. Thus, only the peaks of objects 1, 4, and 5 in the GC, and objects 1 and 3 in the RC exceed the threshold value. As in the previous case, the target is recognized by applying the logical operator AND to the correlation peaks in each channel. Thus, only object 1 is identified as the target without false alarms.

We also analyzed the recognition capability of the system when other objects in test 2 were chosen as targets. Both a CMF and a POF were studied, and complete identification without false alarms was always achieved by using a POF and a threshold of 50% of the maximum in each channel.

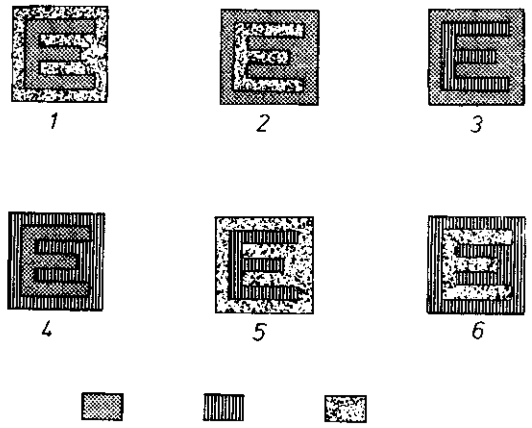

Fig. 6. Test 3.

IV. Character Recognition Regardless of the Color Combination

We now consider the recognition of a character (the character is one of the two sectors that make up the object) regardless of the character–background color combination. As in Section III, here we study the discrimination capability of the method when the test contains objects with the same character and different color combinations and when the test contains objects with different characters. In fact, when a given character is recognized, the information obtained in the first of these two situations is used to solve the second. We analyze the discrimination capability of the method for two characters with different symmetry and area, for example, the letter E and the letter X.

Now the filters are matched to a set of signals that contains the two sectors of the object separately. For each channel, one signal is the character with direct contrast and the other is the square with the character showing inverse contrast. Four filters are used to recognize a given character in a correlator that operates in two (green and red) channels. In the GC one filter is matched to a green character on a black background (direct contrast), and the other filter is matched to a black character on a green background (inverse contrast). Similar filters are used in the RC. POF's are proposed because of their high discrimination capability.

Let us consider recognition of the letter E in test 3 of Fig. 6. This test contains objects only with the letter E but with all six possible color combinations of red, yellow, and green. The intensity distributions of the correlations have been obtained by using a POF matched to the signals with direct and inverse contrast. Table IV lists the values of the correlation peaks. The most intense peaks in Table IV correspond to components with high character–background contrast in the same orientation as in the signal. Thus, when we correlate the scene with the direct contrast signal the green components of objects 2 and 3 and the red components of objects 4 and 6 give the highest peaks. When we correlate the scene with the inverse contrast signal, the green components of objects 1 and 4 and the red components of objects 3 and 5 give the highest peaks. Components with a high contrast in the square edge but with a low character–background contast show some significant peaks when the filter matched to the signal with inverse contrast is used. This is the case for the green components of objects 5 and 6 and the red components of objects 1 and 2, because their external square contrasts are similar to those of the signal, but not their inner character–background contrast. In all these cases, the intensity of the correlation peak does not reach half of the maximum value of each channel. For components with a noticeably different contrast from the signals, no significant peak is obtained.

Each object that contains the letter E has at least one component with high character–background contrast. This component has an amplitude distribution

Table IV. Values of the Correlation Peaks Corresponding to the Recognition of Letter E in Test 3 (Fig. 6)

Channel	Signal Contrast	Intensity Correlation Values						Threshold Value
		Object 1	Object 2	Object 3	Object 4	Object 5	Object 6	
Green	Direct	7.1	**20**	**15**	5.1	4	3.9	V_{GD} = **10**
Red	Direct	5.2	5	5	**17**	6.5	**22**	V_{RD} = **11**
Green	Inverse	**33**	4	2.8	**25**	14	7.4	V_{GI} = **16.5**
Red	Inverse	16	9.7	**29**	1.6	**36**	2.1	V_{RI} = **18**

POF's matched to the letter E with direct and inverse contrast are used in each channel. The values that exceed the threshold value in each row are boldfaced. The subscripts GD, RD, GI, and RI represent green direct, red direct, green inverse, and red inverse, respectively.

Table V. Values of the Correlation Peaks Corresponding to the Recognition of the Letter E in Test 1 (Fig. 2)

Channel	Signal Contrast	Threshold Value	Intensity Correlation Values			
			Object 1	Object 2	Object 3	Object 4
Green	Direct	V_{GD} = **10**	3.6	6.5	1.8	4.3
Red	Direct	V_{RD} = **11**	5	5.5	7.1	4.4
Green	Inverse	V_{GI} = **16.5**	1.3	**32**	1.3	8.1
Red	Inverse	V_{RI} = **18**	12	17	15	1.2

POF's matched to the letter E with direct and inverse contrast are used in each channel. The threshold values of Table IV are considered here. The subscripts GD, RD, GI, and RI represent green direct, red direct, green inverse, and red inverse, respectively.

that is similar to one of the signals introduced above. Thus, in the corresponding channel, it obtains a high correlation peak that permits us to detect the character in the object. To achieve this, we establish a threshold of 0.5 of the maximum correlation peak for each channel and for each filter. These threshold values are listed in Table IV. The correlation peaks that exceed the corresponding threshold are enhanced in Table IV. To determine the presence of the character the logical operator OR is applied to the peaks of each object in the test. If an object gives one or more correlation peaks that exceed the corresponding threshold value, this means that the object contains the character. If an object does not give any correlation peaks high enough to reach the corresponding threshold value, this means that the character sought is not contained in the object. Following these criteria, the letter E is recognized in all the objects of test 3, independent of their character–background color combination, as expected.

In the following we consider the recognition of the letter E in test 1 (Fig. 2), in which the objects have different characters. The filters used in this case are the same as those used for test 3. The values of the correlation peaks are listed in Table V. The threshold values are the same (V_{GD}, V_{RD}, V_{GI}, and V_{RI} in Table IV) as those determined in the previous case for test 3, where all six possible color combinations for objects with the letter E were studied. The values of the peaks that exceed the corresponding thresholds are also enhanced. After the logical operator OR is applied, we conclude that only object 2 contains the letter E. In the RC, when the filter is matched to the signal with inverse contrast, the correlation peaks for objects 1, 2, and 3 reflect the contribution of the square background of their red components whose external contrast is similar to the signal. Nevertheless, the difference in the inner character–background contrast between these objects and the signal means that their correlation peaks do not exceed the threshold value.

Finally, we have applied this procedure to the recognition of the letter X in test 2 (Fig. 3) independent of the color combination of the object. The letter X has a different symmetry from the letter E, and it occupies an area approximately half of the area occupied by the letter E in these objects. For recognition of the letter X we also use four signals in a process similar to that followed for test 3 but with the letter X. Table VI contains the values of the correlation peaks. A threshold of 0.5 of the maximum peak in each channel and for each filter is established. The peaks that exceed the corresponding threshold value are enhanced in the table. After the logical operator OR is applied, the letter X is recognized in all the objects contained in test 2.

From Table VI it can be seen that not all four filters are necessary to achieve the recognition of the letter X. For example, with the information provided by the filters matched to the letter with direct contrast it would be possible to achieve recognition. There are more differences between the edges of the letter X and those of the square than in the case of the letter E. This feature of the objects leads to the recognition of the letter X in less stringent conditions. On the other hand, the decrease of the relative character–background area for the objects with the letter X has not handicapped the detection of this letter.

V. Conclusions

We have studied two problems of recognition of polychromatic images composed by two sectors (a character surrounded by a square background with different colors): (1) the recognition of an object with

Table VI. Values of the Correlation Peaks Corresponding to the Recognition of the Letter X in Test 2 (Fig. 3)

Channel	Signal Contrast	Intensity Correlation Values						Threshold Value
		Object 1	Object 2	Object 3	Object 4	Object 5	Object 6	
Green	Direct	2.7	2.8	**11.7**	**8.7**	**10**	**15.3**	**7.7**
Red	Direct	**9.4**	**16.3**	6.7	**11.7**	3.6	3.7	**8.2**
Green	Inverse	17	7.3	4.5	**34.9**	**45.8**	6.4	**23**
Red	Inverse	**51.4**	4.5	**39.4**	2.7	19.9	9.8	**25.5**

POF's matched to the letter X with direct and inverse contrast are used in each channel. The values that exceed the threshold value in each row are boldfaced.

a given shape and color combination; (2) the recognition of a character regardless of color combination of the object. Different strategies based on multichannel color recognition have been proposed to solve these problems. For the first, the filters were matched to the color component of the object, that is, to the object transmittances obtained by illuminating the object with the wavelengths of the channels. The recognition of the object was achieved when a correlation peak was obtained in each channel at the same point of the output plane. This criterion may be represented by means of the logical operator AND applied to the correlation peaks of all the channels.

For the second problem, two filters were used in each channel. Each filter was matched to one of the two sectors of the object. After the multichannel correlation with all the filters was performed, the character was recognized when a correlation peak was obtained in some of the output planes. This criterion may be represented by means of the logical operator OR.

These strategies have been applied in various situations: scenes that contain objects with different characters and several color combinations, and scenes that contain objects with the same character but differ only in their color combinations. We have also considered some features that may increase the difficulties of the recognition: a high transmission of one of the sectors in all channels and a low character–background area ratio. The recognition of characters with different symmetry and area has been studied. Two types of letter have been considered: E and X. In the first case the edges of the letter are parallel to the square sides. By using two filters in each channel and by applying a threshold equal to 0.5 of the maximum peak in each case, we can recognize the letter E. The same is true for the letter X. Athough the character area in relation to the square area is smaller in this case, the fact that the letter sides are not parallel to the square sides makes recognition easier.

We have shown by computer simulation that the application of these strategies to the information provided by a POF in the different wavelength channels permits us to solve the two recognition problems introduced above. For future implementation of these strategies the technique of computer-generated holography can be used to achieve POF's with the desired information.[16]

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Multichannel rotation-invariant pattern recognition for polychromatic objects using circular harmonic filters

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A method for rotation invariant pattern recognition of polychromatic objects is studied. The recognition of polychromatic objects is obtained by using a multichannel technique. The method is based in the obtention of three correlations for three colour channels (red, green and blue). The rotation invariance is achieved by using circular harmonic filters in each channel.

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1. Introduction

In the last few years, devices for pattern recognition have become more and more important in human activities. Matched filtering is a powerful technique in pattern recognition because the object to be detected can be identified in a scene without scanning. Since the introduction of the Vander Lught matched spatial filter [1], there has been great progress in the generation of such filters for diverse applications in pattern recognition problems (see e.g. ref. [2]). Nevertheless, it cannot detect targets with orientations different from that to which the filter was matched. This is known as the rotation problem, which should be solved in order to achieve better recognition systems. Besides unknown locations and any orientation, the targets to be detected may present different sizes in the input image. The recognition systems are often required to be shift, rotation and scale invariant systems and considerable effort has been made in this direction.

The classical matched spatial filter (CMF) systems are shift invariant but they are in general very sensitive to rotation of the target to be detected. As an average, because it is a function of the shape and characteristics of the object, the angular tolerance can be estimated about 8°–12° with spherical optics systems [3] and about 3°–4° for anamorphic systems [4].

Circular harmonic expansion of two-dimensional complex functions has proven to be a very useful tool for the design and experimental realization of rotation-invariant filters [5,6]. Good practical results may be obtained provided that the choice of the harmonic order (number of the term of the expansion) and the polar coordinate origin taken are both optimized [7,8].

In two recent papers [9,10] we proposed a multichannel correlation process to detect coloured objects, and we studied its discrimination capability with two types of model objects: one type in which the colour distribution inside a square is the feature which discriminates the object. Another type was an alphanumeric character on a square of a different colour. It was compared in a scene which contained the same character on a square with different character-square colour combinations. The method is based on the obtention of three correlations for three colour channels. The combination of the results provided by the three channels allows the recognition of the coloured target without ambiguity. Nevertheless, we showed that for the second type of object a CMF does not provide enough discrimination capability, whereas the use of phase-only filters (POF) pro-

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vides the detection of the target without ambiguity. In a subsequent paper, we experimentally proved the feasibility of the method [11] with the model objects whose shape changes with the wavelength of the illumination beam.

Based on the combination of the two previous methods of pattern recognition, in this paper we propose the use of circular harmonic filters obtained from the expansions of the colour components of the target to be detected, in order to achieve rotation invariant recognition of polychromatic objects.

In sec. 2 we recall the multi-channel correlation technique for coloured object recognition and the method of rotation-invariant pattern recognition, based on circular harmonic expansion of an object. In sec. 3 we present computer simulation results with different type of object. In sec. 4 we give our conclusions.

2. Rotation-invariant colour pattern recognition

2.1. Multi-channel correlation

Colour pattern recognition by multi-channel correlation is based on the fact that the shape and the intensity-distribution of a polychromatic object strongly depend on the illuminating wavelength. The recognition of the object in a scene is achieved using the partial information obtained from the correlations in three monochromatic channels, detecting the object independently in each channel. To this end, three different wavelengths λ_1, λ_2 and λ_3, which cover the visible spectrum are selected. When the polychromatic object is successively illuminated with these wavelengths, the colour components of the object are obtained. We represent a colour component by the amplitude transmittance of the object which in polar coordinates can be written as $h_{\lambda i}(r_1, \theta_1)$ (with $i=1, 2, 3$). Three filters matched to each colour component are recorded and then placed successively in the Fourier plane of an optical correlator working with the wavelength corresponding to the component to be analysed.

Let us suppose that we want to recognize the polychromatic object $h_\lambda(r_1, \theta_1)$ contained in the scene $g_\lambda(r_1, \theta_1)$ and that the operation is performed in a 4-f type optical correlator. Each matched filter is obtained, as usual, recording a Fourier transform hologram of each colour component of the object. If the reference beam impinges on the plate at an angle ψ and f is the focal length of the transforming lens, the term of its transmittance which will give rise to the correlation can be written as

$$\exp[-i2\pi(\sin\psi/\lambda_i)r_2\cos\theta_2]\,H^*_{\lambda i}(r_2/\lambda_i f, \theta_2)\,. \tag{1}$$

$H_{\lambda i}$ is the Fourier transform of $h_{\lambda i}(r_1, \theta_1)$ represented in polar coordinates, the sign * means complex conjugate and (r_2, θ_2) are the polar coordinates in the Fourier plane. In this plane, we have the product of this filter function with the Fourier transform of the scene $G_{\lambda i}(r_2/\lambda_i f, \theta_2)$.

In the correlation plane (r_3, θ_3), the autocorrelation function

$$h_{\lambda i}(r_3, \theta_3) * h_{\lambda i}(r_3, \theta_3) \tag{2}$$

is obtained, centered at the point $r_3 = -f\sin\psi$, $\theta_3 = 0$.

The position of the correlation does not depend on the wavelength. If an auto-correlation peak is detected in one channel it does not necessarily mean that the polychromatic scene contains the coloured object but only its component for the wavelength used in the process. Only when we obtain the peak correlation in the same position for the three channels we can ensure that we have the same object in the scene that to which the filters were matched.

The use of three channels reduces the number of false alarms which can appear when only one wavelength is used and there are polychromatic objects in the scene showing similar colour components under a given illumination. Nevertheless, depending on the object and on the scene, the use of CMF does not always provide enough information to recognize an object without ambiguity, as was showed in ref. [9]. Then, to achieve the recognition in those cases we decided to use POF [10] because of height and width of the correlation peaks allowed better discrimination.

2.2. Rotation-invariant detection

Following Arsenault et al. [12], in this paper we consider that there is rotation invariance of a matched filter output if the modulus of the filter output does not change when the target to be detected is rotated. This definition led to the circular harmonic filter (CMF).

An object $h(r_1, \theta_1)$, given in polar coordinates, can be expressed into its circular harmonic expansion

$$h(r_1, \theta_1) = \sum_{m=-\infty}^{+\infty} h_m(r_1) \exp(im\theta_1) , \qquad (3)$$

where

$$h_m(r_1) = (1/2\pi) \int_0^{2\pi} h(r_1, \theta_1) \exp(-im\theta_1)\, d\theta_1 \qquad (4)$$

is the CH of order m. The same object, when it is rotated an angle α, can be expressed as

$$h(r_1, \theta_1 + \alpha) = \sum_{m=-\infty}^{+\infty} h_m(r_1) \exp(im\alpha) \exp(im\theta_1) . \qquad (5)$$

Let us suppose that the CMF is matched to the single harmonic component of order m, $h_m(r_1) \exp(im\theta_1)$ and in the input plane of a correlator we put the rotated object $h(r_1, \theta_1 + \alpha)$ given by eq. (5). In the output plane of the correlator we have a 2D correlation function. In what follows we will refer to the value at the origin of that function as center correlation [5]. Then, if we denote the center correlation by $C(\alpha)$, at the origin of the output plane we have a complex amplitude value given by

$$C_m(\alpha) = 2\pi \exp(-im\alpha) \int_0^{\infty} r_3 |h_m(r_3)|^2 dr_3 . \qquad (6)$$

Equation (6) shows that the intensity is independent of the angle of rotation, α, providing a full rotation invariance in the sense previously defined. It is very interesting to compare the performance of filters matched to different circular harmonic components, to select the order m that provides the best practical results.

Due to the fact that now we use partially matched filters, we obtain the rotation invariance but at the same time we have a decrease and an enlargement of the peak correlation intensity. So, in practice the center correlation value could be indistinguishable from the value of the correlation function at any other point. When a circular harmonic expansion center verifies that the center correlation is the absolute maximum of the correlation function, then the expansion center is called a proper center [5]. At the beginning, the proper center was found through an iterating method [5,6]. A more appropriate method was later proposed based on the direct calculation of the energy of the CH component for each point of the object [7]. This is the method used here.

3. Computer simulations

3.1. Description of the scenes

In this section, computer simulations of the proposed recognition procedure are presented. For the sake of simplicity, the objects we deal with present red, yellow and green zones; only two channels (red and green) are thus needed in this case to achieve recognition and, without losing generality, the method is easier to check. Moreover, we used the two types of object we previously refered to: in objects type A the colour distribution inside a square is the feature which discriminates the object (fig. 1). The objects type B are composed by alphanumeric characters on a square of a different colour (fig. 2).

Table 1 shows the amplitude transmittance values of the red, yellow and green zones when they are illuminated by the selected wavelengths: $\lambda_1 = 514$ nm (green line from argon laser) for the green channel,

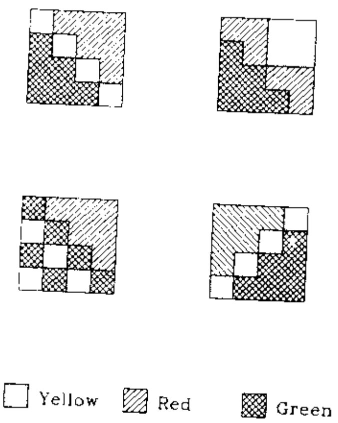

Fig. 1. Colour distribution of a polychromatic scene composed of objects of the first type. The object to be recognized is number 1.

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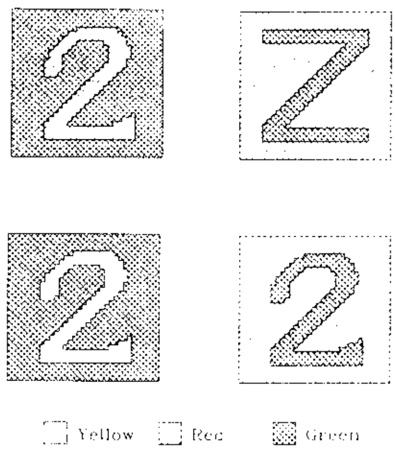

Fig. 2. Colour distribution of a polychromatic scene composed of two very similar patterns of objects of the second type. The object to be recognized is number 1 (red number 2 on a green square). In the scene they are not represented all the objects used in the computer experiment.

Table 1
Amplitude transmittance of the colour zones.

Zone	Amplitude transmittance	
	$\lambda_1=514$ nm	$\lambda_2=633$ nm
red	0.1	0.8
yellow	0.8	0.9
green	0.7	0.2

and $\lambda_2=633$ nm (HeNe laser) for the red channel.

Figure 1 depicts the scene used for the objects type A. The pattern on the left upper corner is that to be detected. Note that in the green channel, the transmittances of yellow and green zones are similar, the same happens with red and yellow zones for the red channel. Hence, ambiguity can arise between objects 1 and 3 in the green channel and between objects 1 and 2 in the red channel. Further, it should be pointed out that object 4 differs from object 1 only in a $\pi/2$ rotation.

Every object transmits the same amount of energy when uniformly illuminated with one of the two wavelengths (λ_1 or λ_2) used in the optical experiment. The energy for the same object in different channels is not the same.

In fig. 2, a scene used for the objects type B is shown. It consists of the characters **2** and **Z** on a small square background. Both characters have the same area. The target to be detected is the pattern on the left upper corner, a red character **2** on a green square. The square has an area three times bigger than the area of the character, so in this case there is no normalization of the patterns. The numerical value of the correlation for every colour combination for **Z** and **2** will be presented. The rotation invariance property of the method for the objects type B is tested by using a scene which contains the same object four times, composed of a letter E in a square, with four different orientations.

3.2. Recognition procedure

The aim of this paper is to obtain a procedure for distinguishing a colour pattern from any other pattern independently of their orientations. We will suppose that objects with different colour distribution are different objects.

The first step in the recognition procedure is to analyze the target pattern to find the center of expansion for the circular harmonic filter, as well as the best CHC order. This step is accomplished by calculating the energy maps for the first circular harmonic orders.

An order is selected so that its energy map exhibits a sharp, high absolute maximum near the geometrical center of the pattern. In this way we prevent the appearance of false alarms and high correlation peaks are obtained. As we choose the absolute maximum of the energy map it is warranted that the correlation peak will be higher than any other side-lobe in the correlation plane and higher than any cross-correlation peak (for objects with the same energy). In the objects we have studied the best harmonic order is $m=4$ for all channels.

Once the proper center and the best CHC order have been chosen, the filter matched to the CHC component is computed. This filter is directly fed into the numerical correlation program.

3.3. Results

Figures 3a and 3b show the output correlation corresponding to the green and red channels, respectively, for the first kind of objects. The intensity cor-

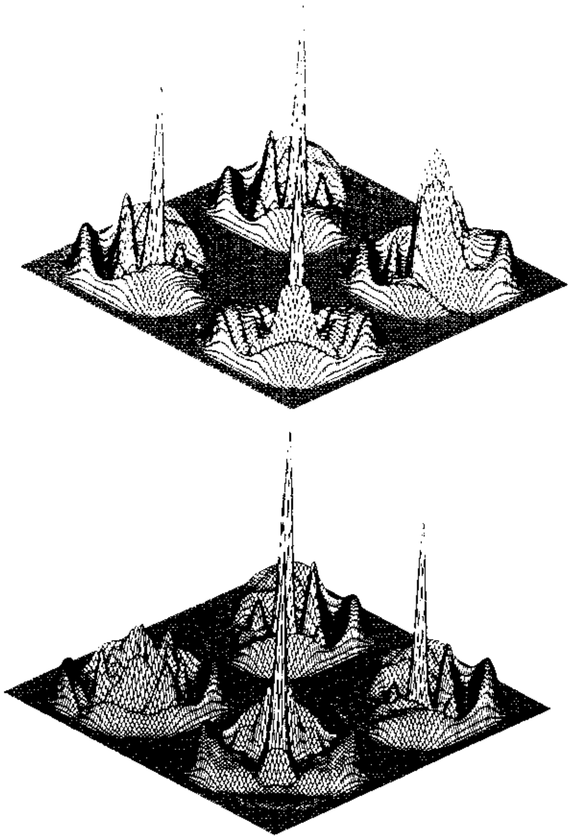

Fig. 3. Intensity of the correlation with a CHC MF between the scene of fig. 1 and the object to be recognized. (a) Green channel, (b) red channel.

Table 2
Values of the correlation peaks for first type objects, obtained with a fourth order CHC MF. Peak values exceeding the threshold value (0.7 of the maximum in each colomn) are enhanced.

Object	Correlation intensity	
	Red channel	Green channel
1	**44.2**	**28.3**
2	**40.0**	19.7
3	15.5	**25.2**
4	**44.3**	**28.3**

relation values are shown in table 2. The filters were matched to the CHC of fourth order in both channels.

From the results of table 2, it can be seen that, as expected, a false alarm is produced for object 3 in the green channel, bringing a correlation value similar to that of objects 1 and 4. The secondary peaks and sidelobes can be rejected taking a threshold of 70%.

In a similar way, in the red channel object 2 may be confused with objects 1 and 4. The same as before a 70% threshold takes out every other peak or sidelobe. From these results it is clear that there is no way to distinguish the target from the information of one single channel.

Once the correlations for both channels are computed the method for detecting the target is to combine the information from both channels. We suppose that a peak is connected with a target if, after thresholding, the peak is common to red and green channels. This is equivalent to performing an "AND" logical operation between the peaks on both channels. Using a 70% threshold we obtain the recognition of objects 1 and 4 of the input image.

As mentioned early the POF enhances the performance of the filter, by providing better discrimination and higher correlation peaks. We have tested it in the case of the CHC filter for colour objects in fig. 1. The correlation on both channels is depicted in fig. 4, and the numerical values of the correlation peaks in table 3.

The numerical value in table 3 show that the absolute values of the peaks are higher than those obtained with CHC filters, due to the greater efficiency of POF. The correlation peaks are sharper than with CHC filters, but wider than those for a classical matched filter due to the greater size of the impulse response.

We see that the ambiguity between objects 1 and 3 in the green channel and between objects 1 and 2 in the red channel remains, it still being impossible to discriminate by working in a single channel. Now 60% threshold is enough to isolate the valuable peaks.

Using the same procedure as in the case of classical CHC filter, that is, by employing the information provided by the two channels, we obtain the recognition of objects 1 and 4.

If we compare with previous results [9] we can conclude that the CHC filter behaves in a similar way to the CMF, being able to detect a coloured object in a polychromatic scene with slightly lower level of discrimination, particularly if we compare the results obtained with POF. But, as it is a filter matched to a CHC, it provides a full rotation invariant colour

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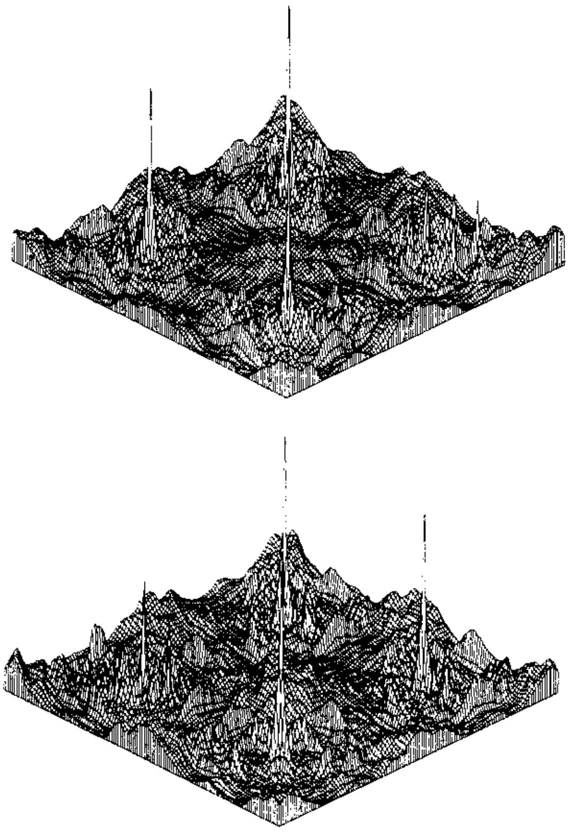

Fig. 4. Intensity of the correlation with a CHC POF between the scene of fig. 1 and the object to be recognized. (a) Green channel, (b) red channel.

Table 3
Values of the correlation peaks for first type objects, obtained with a fourth order CHC POF. Peak values exceeding the threshold value (0.6 of the maximum in each column) are enhanced.

Object	Correlation intensity	
	Red channel	Green channel
1	**380**	**297**
2	**357**	108
3	208	**273**
4	**386**	**291**

pattern recognition, as could be expected [5,6]. A threshold of about 70% is enough to avoid false alarms with CHC MF (60% in case of CHC POF).

To analyse the performance of the CHC filters for the second kind of objects, we verified that they provide a full rotation invariance detection. To do this, we took a scene consistinf of te letter E in a square with four different orientations. If we take the origin of the angle of orientation when the letter E is in the vertical position and we rotate in counterclockwise direction, the four objects of the scene are oriented at 0°, 180°, 225° and 270°, respectively.

The filter was matched to the CHC of fourth order corresponding to the pattern in its vertical position. Table 4 shows the results obtained with a CHC MF, and table 5 with a CHC POF.

From these tables, we see that full rotation invariance is obtained. The difference for object 3 in the intensity peak value (particularly with phase filters) is due to the sampling in the digital picture. This is more evident for POF where the high spatial frequencies have a greater weight than with CMF.

The second step consisted in the calculation of the correlation values for the objects previously described. We recall that the target to be detected is a

Table 4
Values of the correlation peaks for a scene composed of a green letter E on a red square with four different orientations. The filter was matched to the fourth order CHC of the pattern in its vertical position.

Object (orientation)	Correlation intensity	
	Red channel	Green channel
1(0°)	120	145
2(180°)	120	145
3(225°)	122	162
4(270°)	120	145

Table 5
Values of the correlation peaks for a scene composed of a green letter E on a red square with four different orientations. A POF was matched to the fourth order CHC of the pattern in its vertical position.

Object (orientation)	Correlation intensity	
	Red channel	Green channel
1(0°)	520	195
2(180°)	503	189
3(225°)	535	255
4(270°)	499	186

red character **2** on a green background. Table 6 shows these results with a CHC MF. Each object is designated after the character name followed by the colour of the character and the colour of the square. As we see from these results it is not as easy as in the former case to distinguish the target mainly due to the existence of objects with correlation values higher than that of the target.

If we have no a priori knowledge of the scene, we should impose a threshold, in principle the same for both channels. The threshold should be relative to the maximum value on the correlation scene, which is no longer the peak due to the target, because of the lack of normalization. In this case a valuable threshold should be between 0.68 and 0.55 of maximum in each channel. A greater threshold would not detect the target and a smaller one would give false alarm. The range of limits is very narrow, especially if the scene is unknown. In a real optical experiment due to the coherent noise it could be difficult to find the optical threshold. Fortunately this situation may be greatly improved by the use of POF.

Note that for CHC filter the whole energy of an object is not as important as in the case of CMF, because of the existence of negative zones on both real and imaginary parts of the impulse response. They have, in fact zero mean, so a uniform zone of the scene would give a zero value correlation, regardless of the value of the uniform area. For a CMF, discrimination of this type of object would be impossible (see ref. [7]), one of the reasons is because the transmittance of the uniform yellow square is much higher than that of the target on both channels. As a major drawback the intensity of the sidelobes, relative to peak value is increased, bringing a more noisy correlation.

Although the CHC filter has only partial information about the object to be detected, its discrimination ability can be greater than with the filter matched to the whole object. This can be seen by comparing the results obtained in ref. [6] for objects type B, using a CMF, with those corresponding to the same colour combination (table 6), with the character **2**, when using a filter matched to the fourth order of the CH expansion. In the last case, with a threshold of 60% we detect the target without false alarms, which is not the case with CMF.

In table 7, the correlation intensity values for the CHC POF are given. Under the same assumptions ast with the CHC MF, the useful threshold range if

Table 6
Values of the correlation peaks obtained with a scene composed of second type objects. Two very similar patterns are also compared (either number **2** or letter **Z** on a square). The asterisk denotes the pattern to be recognized. The filter was matched to the fourth order CHC of this pattern. Peak values exceeding the threshold value (0.6 of the maximum in each column) are enhanced.

Object	Correlation intensity	
	Red channel	Green channel
2RG*	**91.6**	**320.0**
2RY	59.2	**426.8**
2GR	**102.0**	58.3
2GY	**135.0**	165.0
2YR	58.4	77.0
2YG	**119.8**	112.0
ZRG	74.0	236.0
ZRY	58.7	**315.0**
ZGR	66.9	45.5
ZGY	**86.2**	151.0
ZYR	58.5	60.6
ZYG	**96.9**	123.0

Table 7
Values of the correlation peaks obtained with a scene composed of second type objects. Two very similar patterns are also compared (either number **2** or letter **Z** on a square). The asterisk denotes the pattern to be recognized. A. POF was matched to the fourth order CHC of this pattern. Peak values exceeding the threshold value (0.5 of the maximum in each column) are enhanced.

Object	Correlation intensity	
	Red channel	Green channel
2RG*	**758**	**2812**
2RY	324	**3752**
2GR	**589**	643
2GY	**762**	1193
2YR	321	860
2YG	**998**	739
ZRG	331	1557
ZRY	323	**2074**
ZGR	**450**	416
ZGY	**586**	1005
ZYR	289	580
ZYG	446	824

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from 0.33 to 0.75. If we take a threshold of 50%, there is recognition of the target to be detected without any ambiguity, making use of the information provided by the two channels. Taking into account the values of the correlation peaks, we can see the importance of the character shape and the colour combination character - background.

4. Conclusions

We propose a technique for the recognition of colour objects independently of their angular orientation. This is based on the study of the successive correlations with filters matched to one CHC of the object transmittance for different wavelengths, that is, of the colour component of the object. The coincidence of the correlation peaks in the different wavelength channels allows the identification of the target to be detected.

The method has been applied to two different types of colour objects: in objects type A, the colour distribution inside a square is the feature which discriminate the object. Objects type B are composed by an alphanumeric character on a square of a different colour.

Concerning the filters, CHC MF and CHC POF have been used. The discrimination capability of both filters has been studied with the two types of objects. For the design of these filters, the order of the CHC selected for each wavelength may be different. In general the center for the CH expansion is the same for objects with only colour variation. For objects also presenting shape variation when the wavelength of the illumination beam changes, it can be different for each colour component of the object, because the geometrical center can also move when passing from one colour component to another. In our case we selected the fourth order because it presents a maximum in the energy maps.

Objects type A, independently of their orientations, can be identified by CHC MF and CHC POF. In the last case the detection conditions are more relaxed. The discrimination capability of these CHC filters is only slightly lower than in the case of using filters matched to the whole target, as can be seen with from results in refs. [9,10].

Objects type B, independently of their orientations, can also be identified by this technique. Moreover, the results with CHC MF can be better than with a CMF (ref. [10]). As in the previous case, the use of CHC POF improves the results. When comparing the two sets (with 2 and z) of objects of the second type, we can see that the discrimination between objects with different symbols inside the square is very clear with CHC POF, due to the enhancing of high frequency information.

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