Single-channel polychromatic pattern recognition by the use of a joint-transform correlator

David Mendlovic, Meir Deutsch, Carlos Ferreira, and Javier García

We present a single-channel system for color image recognition that is based on a joint-transform correlator setup. The color images are encoded as phase and amplitude functions, inspired from the Munsell color representation. A real-time implementation of the new codification method can be achieved by the use of a spatial light modulator operating in phase-only modulation mode. We determine the optimal codification for a linear color-phase code. Its performance is compared with a conventional multichannel correlator by means of computer simulations. Experimental results are also presented. © 1996 Optical Society of America

1. Introduction

One of the main trends in optics has been that concerning pattern recognition because of the ability of an optical system to perform a correlation (or convolution) in real time. However, most of the optical implementations, based either on the 4-*f* VanderLugt correlator[1] or on the joint-transform correlator (JTC),[2] deal with monochromatic images. In real images the color information can be a fundamental component for image analysis. Note that, when speaking of color pattern recognition, we mean that the system should recognize similarities between the shape distributions of each color. Positive recognition means full shape similarity between the input and the reference images in each color distribution. The inclusion of the color information in an optical-correlator scheme has concentrated large efforts in the last years. Several methods[3–9] have been devised for this purpose, most of them based on a multichannel approach.

The multichannel approach represents a color image as intensity information in a few separate channels [typically red, green and blue (RGB) channels], defined by the transmittance of the image for a set of predefined wavelengths. These monochromatic images (every channel has its own wavelength) are separately correlated in each channel. The output plane consists of a set of superimposed correlation distributions, one for every channel, each with a different wavelength. This wavelength multiplexing has been implemented by the use of two primary methods. The first method involves spatial separation of the spectra of each channel by means of a dispersive element. This is achieved with a tricolor grid placed at the input plane[3,4] or by the use of the grating structure of a color liquid-crystal television (LCTV).[5] The Fourier plane consists of spatially separated spectra, each one of a different wavelength corresponding to a different channel. The correlation can be produced with a set of matched filters, one for each different spectrum, or with a JTC. The second method does not spatially separate the spectra and does use a single, optically recorded, matched filter. A proper choice of the hologram's carrier frequencies for each channel avoids overlap among the correlation outputs. This method was demonstrated with both a conventional matched filter and with a phase-only filter.[6,7]

The multichannel approach implies that the output for each channel must be analyzed separately to search for possible correlation peaks for every channel, and then the separate results must be blended to render the final detection decision. Instead of using several channels it is possible to reduce the information to a single channel, while most of the discrimi-

D. Mendlovic and M. Deutsch are with the Department of Electrical Engineering–Physical Electronics, Faculty of Engineering, Tel-Aviv University, Tel Aviv 69978, Israel. C. Ferreira and J. Garcia are with the Department Interuniversitari d'Optica, Universitat de Valencia, Burjassot 46100, Spain.

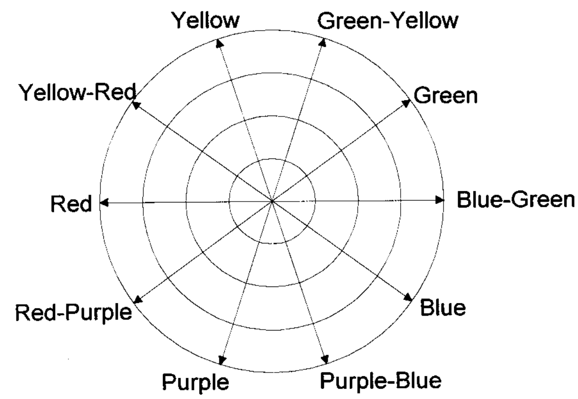
Received 27 November 1995; revised manuscript received 20 June 1996.
0003-6935/96/326382-08$10.00/0

nating information is maintained.[8] This way the analysis is simplified, at the price of complex preprocessing of the input image.

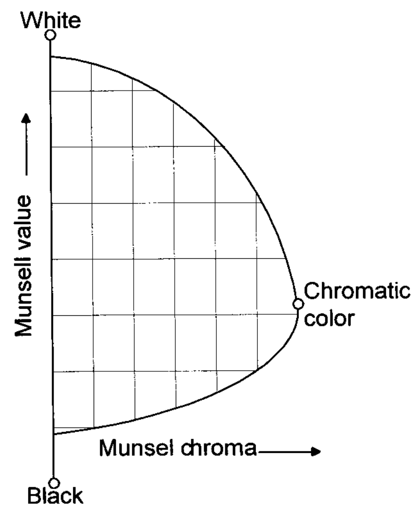
One can further simplify the analysis from the experimental point of view by coding the color scene as a phase-only distribution that is used as the input plane for a VanderLugt correlator.[9] This modification permits the use of a single channel for the input image and for the output correlation. As a result a more compact and feasible system, permitting an easier analysis of the output, is obtained.

The VanderLugt correlator uses a complex spatial-filter synthesis and involves the relatively accurate alignment of the spatial filter, which is difficult to achieve in real time. On the other hand, the JTC has become popular in recent years owing to the possibility of real-time implementations.[10,11] This possibility is due to the great technological improvements in spatial light modulator (SLM) devices, especially in low-cost LCTV's, which can operate either as amplitude modulators or as phase modulators.[12] Thus, although difficult to implement, one can directly synthesize a phase and amplitude function by the alignment of two such LCTV's in cascade. Many methods have been devised to improve the light efficiency and the correlation-peak sharpness of the JTC system. One of these methods[13] encodes the amplitude distribution of the input plane as a phase-only input function.

This paper extends the codification of the input color image as a phase-only distribution to the JTC configuration. Hence, we add the advantages of a single-channel approach to those provided by the real-time possibilities of the JTC. Sections 2 and 3 provide the principles of the color-phase code and present different codification possibilities. Section 4 describes the optical setup, and Sections 5 and 6 provide computer simulations and experimental results, respectively.



(a)



(b)

Fig. 1. Organization of the Munsell colors (a) with a constant value and (b) with a constant hue.

2. Color-Phase Code

Most color-image-acquisition systems (such as CCD cameras) generate as output three arrays. Each array represents the intensity value of one RGB component of the image. Although the RGB color code is the most usual one, there are many other color codes, such as the Munsell color code.[14]

The Munsell color system is based on principles of human color perception represented as a color solid. This method represents the color through three components: hue (dominant wavelength), value (intensity), and chroma (colorimetric purity). The horizontal cross section of a Munsell color solid, which represents the constant-value chart, is shown in Fig. 1(a). Colors of constant hue are shown along the radial lines intersecting at the center point, which represents gray, whereas colors of constant chroma lie on the concentric circles. Figure 1(b) represents the constant-hue chart (vertical cross section of the Munsell color solid). The colors along any row are perceived as equally bright, whereas along any column the colors are perceived as having the same chroma.

Many practical recognition systems have a limited set of colors in the image, thus using only a part of the entire color solid. In this paper we propose to combine the hue information with the chroma information in the same variable. This variable represents all the chromatic information of the image. The chromatic information is ordered according to the Munsell hue sequence, and in the case of colors with same hue they are ordered by their chroma. Thus we represent all the color information of an image with only two variables: a combined chromatic variable and the intensity.

Based on the inspiration of the Munsell color code, the combined chromatic variable is encoded into phase information, whereas the intensity of the original image is encoded into amplitude information. The color image, encoded into amplitude and phase information, can then be used as input to our optical color-recognition setup.

Unfortunately, representing both amplitude and phase information can be difficult to implement. However, in practical pattern-recognition systems further simplification can be added. The color images

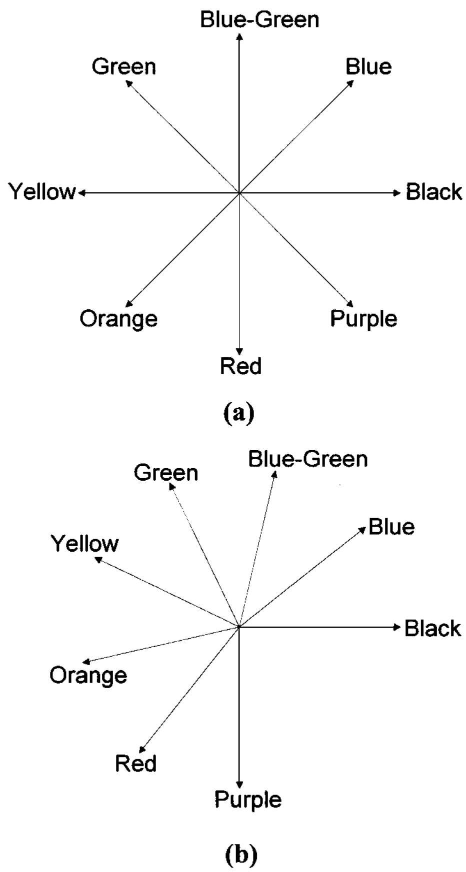


Fig. 2. Possible color-phase codes for eight-color images for (a) a 315° phase range and (b) a 270° phase range.

may have nearly constant lightness values throughout the whole scene, hence the intensity information of our image can be neglected. This simplification can be compensated by the addition of more colors to the combined chromatic variable, especially for the achromatic colors (black, gray, or white), which cannot be represented without taking into account the intensity. We therefore may reduce the encoded color image into a single variable that can be represented as amplitude information in the input plane of the JTC. However, to improve the light efficiency of the correlation peak,[13] we codify this single variable as a phase-only input to our JTC setup.

The combined chromatic variable can be encoded into phase information by the use of several codification schemes. These codifications are referred to as color-phase codes. They differ in the phase range used and in the division of this phase range among different colors. We examine only linear codification methods here, i.e., the usable phase range θ_{MAX} is divided equally among the encoded colors. Thus, the phase separation between adjacent colors $\Delta\theta$ is

$$\Delta\theta = \frac{\theta_{\mathrm{MAX}}}{N - 1}, \tag{1}$$

where N is the number of different colors in the image. Figures 2 and 3 present two examples of possible color-phase codification methods for eight and four colors, respectively.

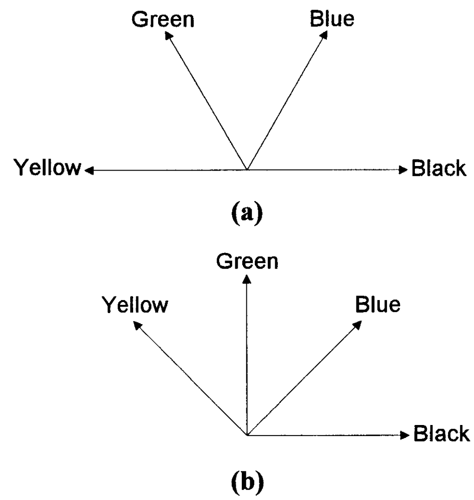


Fig. 3. Possible color-phase codes for four-color images for (a) a 180° phase range and (b) a 135° phase range (the optimal phase range).

While one implements the color-phase code there are sometimes difficulties to achieving a phase range of 360° with phase-only SLM's. Furthermore, a 360° phase range is not always the optimal choice, and sometimes it causes problems of false target identification, as shown in Section 3.

3. Optimal Phase Range

We now investigate this problem of false target identification by using an input image that is the original reference scene after some color transformation. This color transformation changes the original colors of all the shapes in the scene by rotation of the color-phase code by several steps, as demonstrated in Fig. 4. Note that this color-code rotation, which affects every color in the image, provides the minimum change in the output correlation. For instance, the exchange of only two colors in the color-phase code would result in a larger decrease of the correlation value.

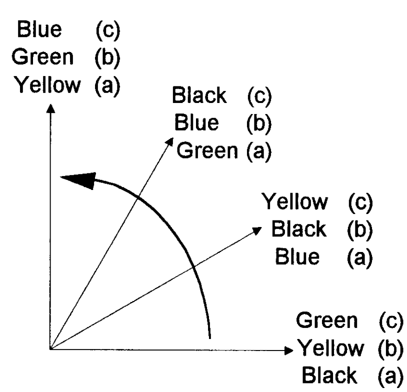


Fig. 4. Image color-code rotation: (a) the original color-phase code, and color transformations for (b) a one-step and (c) a two-step counterclockwise rotation.

During the performance of the cross correlation between the phase-encoded reference image and the input image, such a color transformation may result in false target identification, depending on the phase range used in the color-phase code. The most obvious case of this phenomenon happens when a phase range of

$$\theta_{\mathrm{MAX}} = 360° - \Delta\theta \tag{2}$$

is used. All the colors of the input image will be phase encoded as the phase of the reference image plus a constant phase value throughout the whole scene. Hence, the center value of the cross correlation will be the same as that of the autocorrelation, except for a constant phase factor. A conventional intensity detector will not be able to make a distinction between them. The color-phase code of Fig. 2(a) is an example of such a problematic phase range.

Even using a smaller phase range might cause a similar problem. For this color-transformation case, the correlation intensity value at the origin is

$$C_M(0, 0) = \left| \iint f_{\mathrm{ref}}{}^*(x, y) f_{\mathrm{ref}}{}^M(x, y)\mathrm{d}x\mathrm{d}y \right|^2, \tag{3}$$

where f_{ref} is the reference image and $f_{\mathrm{ref}}{}^M$ is an input image that is identical to the reference image but has undergone a color-code rotation of M steps.

Both images are phase-only functions, therefore Eq. (3) can be simplified. The autocorrelation intensity value at the origin (obtained when M equals zero), under the assumption of a discrete image, is

$$C_0(0, 0) = \left| \iint |f_{\mathrm{ref}}(x, y)|^2\mathrm{d}x\mathrm{d}y \right|^2 = \sum_{k=1}^{N} P_k{}^2 = L^2, \tag{4}$$

where P_k is the number of pixels in each one of the color shapes composing the scene and L is the total number of pixels in the scene. The autocorrelation center intensity is not affected by the usable phase range. The cross-correlation intensity at the origin can be calculated by use of the fact that the product of f_{ref} and $f_{\mathrm{ref}}{}^M$ contains only two phase values. The shapes whose colors are displaced without passing the maximum phase range have a phase value of $M\Delta\theta$. On the other hand, if the transformation involves crossing the maximum phase range, the shapes contain a phase of $(M - N)\Delta\theta$. Hence the cross-correlation center intensity value is

$$C_M(0, 0) = \left| e^{iM\Delta\theta} \sum_{k=1}^{N-M} P_k + e^{i(M-N)\Delta\theta} \sum_{k=(N-M)+1}^{N} P_k \right|^2. \tag{5}$$

Equation (5) represents a vectoric sum of two phasors, as shown graphically in Fig. 5. Because the input image $f_{\mathrm{ref}}{}^M$ should be rejected, we must decrease the value of $C_M(0, 0)$ as much as possible. This goal is achieved by the choice of an optimal phase separation between adjacent colors, $\Delta\theta_{\mathrm{opt}}$,

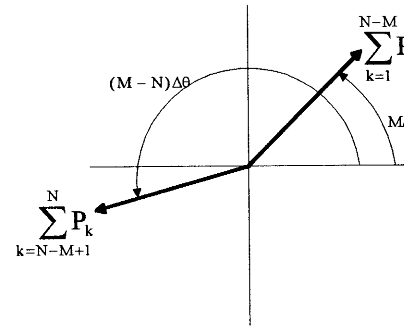


Fig. 5. Graphic representation for the vectoric sum of the two phasors of Eq. (5).

which will oppose the two phasors, i.e.,

$$(M - N)\Delta\theta_{\mathrm{opt}} - M\Delta\theta_{\mathrm{opt}} = 180°. \tag{6}$$

By using Eqs. (1) and (6) we find that the optimal phase range $\theta_{\mathrm{MAX}}{}^{\mathrm{opt}}$ is

$$\theta_{\mathrm{MAX}}{}^{\mathrm{opt}} = \frac{N - 1}{N}(180°). \tag{7}$$

It can be seen from Eq. (7) that the optimal phase range is much lower than 360°. The optimal phase range for a linear color-phase code is 90° for images with only two colors and approaches 180° for images with a large number of colors. The correlation performance of different color-phase codes (utilizing different phase ranges) for the color-rotation case described above is demonstrated in Section 5.

4. Optical System

The classical JTC configuration uses an amplitude-only transparency in its input plane. When applying the color-codification method presented in Section 2, we need to represent both phase and amplitude information (or phase-only information for the simplified case of the color-phase code) in the reference image and in the input image. This complex input plane cannot be achieved by the use of a simple transparency. Displaying a phase and amplitude function can, in principle, be achieved by the use of two SLM's in contact, one working in the phase-only mode and the other in the amplitude-only mode. However, this method is noisy and complex and results in low performance.

A simpler method is to use an amplitude-only modulator (or transparency) and to encode the complex input function by the use of the complex reference method introduced in Ref. 15. With this method we encode the phase and amplitude information of both the input and reference images through a computer-generated hologram (CGH). After the input beams pass through a Fourier-transform lens, we obtain the joint spectrum of the two encoded images (the reference and the input images) in each one of the diffraction orders. We use the first diffraction order as the joint-spectrum plane. A second Fourier transform provides the desired correlation between the complex

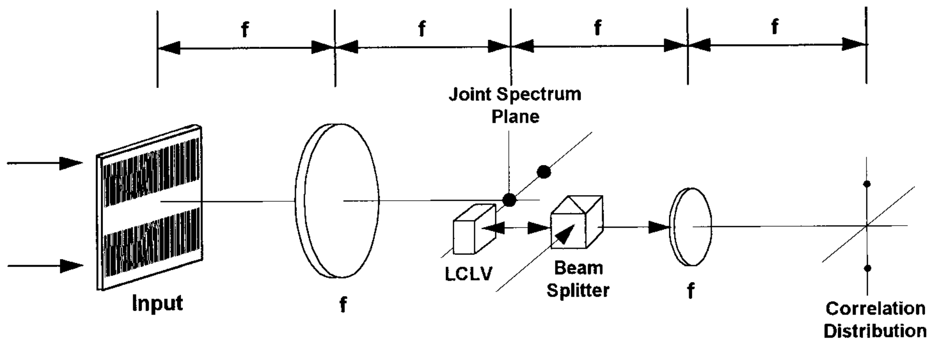


Fig. 6. Schematic diagram of the setup for a real-time JTC.

reference image and the complex input image in the output plane of the JTC at the location of the $+1$ and -1 diffraction orders.

An experimental setup that is able to perform a complex input JTC operation in real time is shown in Fig. 6. This setup is the conventional JTC configuration with a liquid-crystal light valve (LCLV) at the joint-spectrum plane. The readout beam of the LCLV is proportional to the intensity of the joint spectrum, thus generating the correlation distribution of the two input functions in real time by virtue of the second Fourier transform. The input plane is a transparency or an amplitude-only LCTV, utilizing the above-mentioned complex reference method. Although the LCTV has a limited space–bandwidth product, current LCTV technology is able to represent such a CGH-encoded input plane for small images with few colors. The LCTV's resolution limits the number of colors because of the CGH encoding, which spreads each color-image pixel into several LCTV pixels (as many pixels as the number of colors). When the simplified case of the phase-only codification method is used, the input plane can be represented by a phase-only LCTV, and the system becomes collinear without involving off-axis diffraction orders. A gray-level representation of the input plane can be displayed directly on the phase-only LCTV, hence each color-image pixel is mapped onto a single LCTV pixel. Such a system can represent larger images, with a number of colors that is limited only by the characteristic of the LCTV.

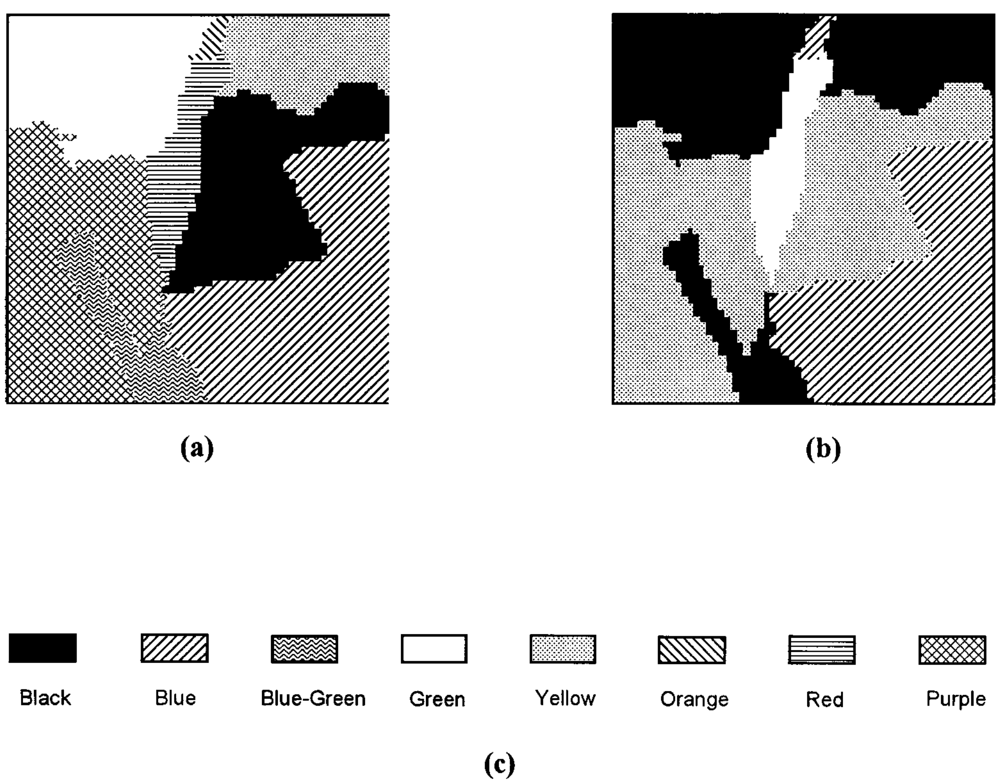
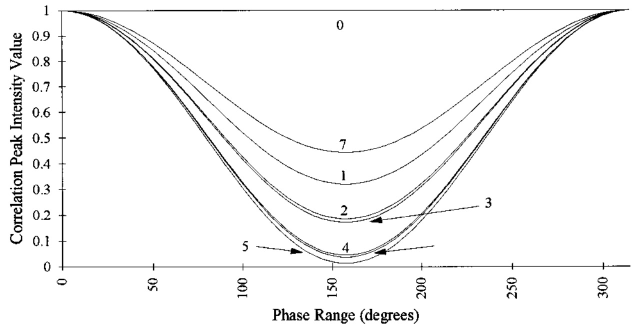
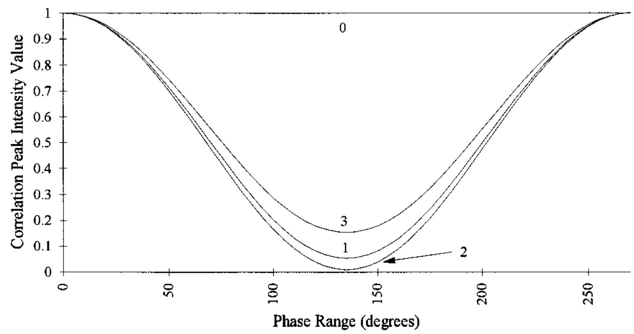


Fig. 7. Map of the Middle East used in the experiment and the computer simulations (a) with eight colors and (b) with four colors. (c) The color key.



(a)



(b)

Fig. 8. Computer-simulation results for the correlation center intensity values versus the phase range for different color-code rotation steps. The numbers near each curve indicate the rotation steps. (a) An eight-color scene and (b) a four-color scene.

5. Computer Simulations

We simulated a JTC setup utilizing the color-codification method proposed above. The scene is a color image of a map of the Middle East, centered around Israel, as shown in Fig. 7(a). This scene consists of eight different shapes, each one with different color, representing six countries and two seas. We also generated a four-color version of this scene by filling in a few shapes with the same color, as shown in Fig. 7(b).

The scene has a constant lightness (except for black) value, therefore we can neglect the intensity and encode the colors (including black as a color) using the phase-only codification method. The graphs in Fig. 8 present the simulation results for the correlation center intensity values versus the phase range for the color-code rotation case described in Section 3. The cross-correlation results are normalized to the autocorrelation center value. It can clearly be seen that the simulation results comply with the optimal phase range of Eq. (7).

When we use the optimal phase range there is no chance of false target identification because the cross correlation is quite small. Tables 1 and 2 show the correlation results obtained by our single-channel method and by a conventional multichannel method for eight and four colors, respectively. The data are normalized to the autocorrelation value. Multichannel correlation center values are obtained by the addition of the correlation intensities of the three channels. It can be seen from the tables that the results are quite similar for both methods.

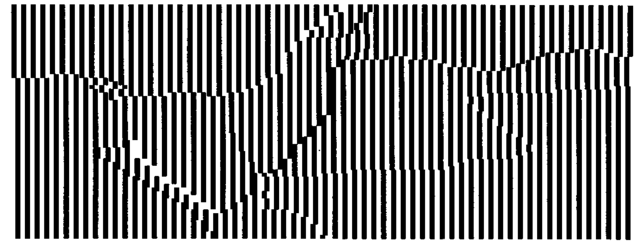


Fig. 9. Amplitude-only input-plane representation of an eight-color phase-encoded scene obtained by the use of the complex reference method.

6. Experimental Results

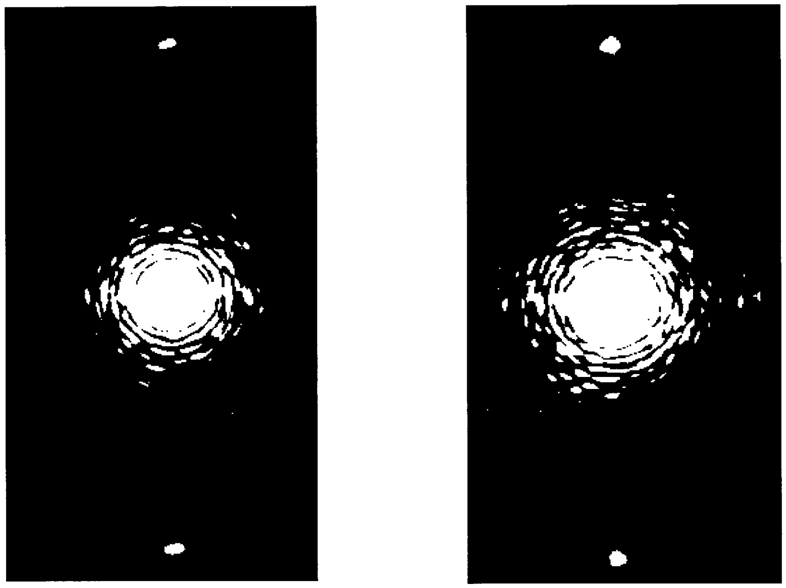
The proposed color-phase code method was tested experimentally for the same scenes that were used in the computer simulations. Both phase-only encoded images (reference image and input image) were implemented as CGH's by the use of the detour-phase method developed by Lohmann and Paris,[16] with a resolution of 64×64 pixels. Four or eight levels of phase were used, depending on the number of colors in the scene. An example of such CGH implementation for an eight-color phase-only-encoded scene is shown in Fig. 9. This CGH is codified with a horizontal carrier frequency, hence the joint spectrum is generated at the diffraction orders in the x direction,

Table 1. Correlation Intensity Values for Eight-Color Images with Different Rotation Steps for a Color-Phase Code JTC Utilizing the Optimal Phase Range (157.5°) and for a Conventional Multichannel Correlator

	Correlation Center Intensity Value	
Rotation Step (M)	JTC Optimal Color-Phase Code	Multichannel Correlator
0	1.00	1.00
1	0.32	0.29
2	0.19	0.19
3	0.17	0.07
4	0.05	0.02
5	0.01	0.06
6	0.04	0.31
7	0.44	0.31

Table 2. Correlation Intensity Values for Four-Color Images with Different Rotation Steps for a Color-Phase Code JTC Utilizing the Optimal Phase Range (135°) and a Conventional Multichannel Correlator

	Correlation Center Intensity Value	
Rotation Step (M)	JTC Optimal Color-Phase Code	Multichannel Correlator
0	1.00	1.00
1	0.05	0.01
2	0.01	0.00
3	0.15	0.36



(a) **(b)**

Fig. 10. Autocorrelation plane for the color-phase code shown in (a) Fig. 3(b) and (b) Fig. 2(a).

whereas the desired correlation is achieved at the $+1$ and -1 diffraction orders in the y direction. These CGH implementations of the reference image and the input image were placed in the input plane, one below the other, with adequate vertical separation. The amplitude-only input plane was printed directly onto film at its final size of 10 mm $\times$ 10 mm with a Scitex Corporation Dolev-PS plotter.

We performed the autocorrelation experiments using these phase-encoded scenes with four or eight colors and employing several phase ranges. The autocorrelation results for all cases were excellent, as can be seen from Figs. 10 and 11, which show quite sharp and distinct autocorrelation peaks.

7. Conclusions

A novel approach for performing polychromatic pattern recognition by the use of the JTC configuration has been presented. This method is single channel, as opposed to the usual multichannel configurations for color pattern recognition, thus resulting in a more compact and simpler correlator.

The color images were encoded as phase and amplitude functions. Usually the amplitude information can be neglected and phase-only functions can be used to encode the color images.

We presented several possible color-phase codification methods and examined their correlation capabilities both experimentally and with computer simulations. We determined the optimal phase-range value to provide the best false-target rejection for the case of a linear color code. The correlation results obtained by the use of this optimal phase range are quite similar to those of a conventional multichannel correlator, but the single-channel cor-

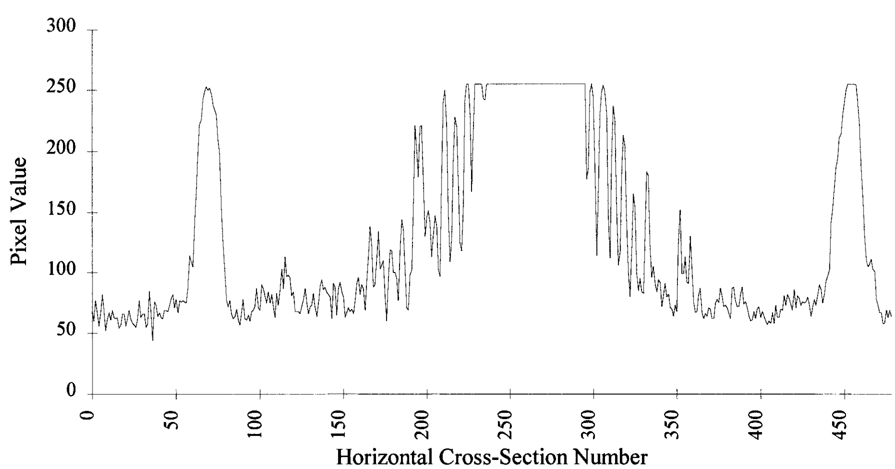


Fig. 11. Vertical cross section through the autocorrelation plane shown in Fig. 10(a) and displaying the correlation distribution.

relator involves a much simpler experimental system.

C. Ferreria acknowledges a grant from the Israeli–Spanish cultural agreement; J. Garcia acknowledges a grant from the Universitat de Valencia. This work was partially supported by Comision Interministerial de Ciencia y Tecnologia under the project TAP93-0667-103-03.

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