Color encoding for polychromatic single-channel optical pattern recognition

David Mendlovic, Pascuala García-Martínez, Javier García, and Carlos Ferreira

The common multichannel system for recognizing colored images is replaced by a color-encoded single-channel system. A method inspired by the Munsell color system is used for encoding the different colors as phase and amplitude functions. It is shown that for many practical cases the phase information part of the color code is sufficient for obtaining good results. An implementation based on a liquid-crystal television panel that works in a phase-modulation mode is suggested. Computer simulations that demonstrate the capabilities of the suggested method are given as well as a comparison with previously published multichannel performance.

Key words: Color pattern recognition, phase encoding. © 1995 Optical Society of America

1. Introduction

Modern vision systems commonly work with color images. Conventional optical processing approaches such as the 4-*f* VanderLugt correlator[1] regularly take into account only the monochromatic information of the objects. During the past decade, some efforts have been made to introduce polychromatic images into the optical processing systems. All of them are based on the fact that every polychromatic image can be represented as a superposition of three monochromatic images, for instance, the well-known red-green-blue (RGB) representation. Yu[2] suggested performing a wavelength multiplexing of the three different channels, in which every channel acts as a conventional coherent VanderLugt correlator. Three colinear coherent sources (RGB) were used. A diffraction grating was placed in contact with the colored input transparency. Because of this grating in the Fourier plane, the spectral distributions of the different colors appeared separately (spatial multiplexing). Later, this technique was implemented in real time by use of a magneto-optics spatial light modulator.[3]

Another multichannel system for color-image recognition is based on a classification and identification process.[4] This correlator uses input incoherent illumination, and the color information is decomposed into three channels, RGB. In the filter generation a transform that extracts the feature of a class and passes from observation space to decision space with minimum error is considered. The obtained results proved that the classification power of the algorithm increases when the filter contains information about the shape and the color instead of information about the shape only.

References 5–8 discuss several mathematical formulations for multichannel colored pattern recognition that are based on transforming the three-dimensional vector color image into a two-dimensional vector. An optimal generalized color plane was found and used for obtaining a filter with more discrimination capability. In Refs. 9 and 10 an improved multichannel color-image-recognition process is presented. 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 and phase-only filters were numerically simulated for different types of objects. Recently, laboratory experimental results that proved the obtained simulations were published.[11,12]

New investigation directions are always affected by the state-of-the-art device technology. For optical pattern recognition the bottleneck device has been, for years, the spatial light modulator (SLM), for encoding either the input or the filter patterns. Recently, multilevel phase-only modulators became widely used, especially in optical correlators. These are the liquid-crystal light valve,[13] the liquid-crystal television,[14,15] and the deformable-mirror array de-

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vice.[16] In most of the cases, these modulators can be used as amplitude modulators, possibly with decreased efficiency.

The possibility of encoding the input image of an optical correlator as a phase function was originally hinted at by Juday *et al.*[17] Later studies related to this phase-input-encoded approach studied various aspects of this approach; for example, the effect of phase distortion,[18] Horner efficiency,[19] and the use of these phase-encoded input planes for improving energy efficiency in the correlation peak.[20]

In the following investigation we suggest replacing the multichannel approach for color image recognition with an input-plane phase or a phase/amplitude-encoded pattern. The suggested system uses a single-channel setup, and thus it is more compact and reliable than the multichannel approach. In addition, no digital postprocessing steps are required. In Section 2 the detection algorithm and the filter-generation procedure of the suggested system are described. Two cases are treated, phase and amplitude encoding of the colored image and phase-only encoding. Some considerations relating the color-code image and a specific suggestion (the Munsell color system) are discussed in Section 3. Section 4 gives results that are obtained by computer simulations for the phase and the amplitude codes and for the phase-only code. In addition, a comparison with previously published multichannel system performance[11,12] is given in order to show the superiority of the new approach.

2. Description of the Suggested System

Figure 1 shows a conventional 4-f VanderLugt correlator.[1] This scheme is suggested for performing color pattern recognition. At the input plane the encoded pattern $f_e(\overline{X})$ is placed and illuminated by a collimated coherent input beam. Note that $f_e(\overline{X})$ could be a complex function (phase and amplitude). At the filter plane a matched filter $H(\bar{f}_x)$ [with the filter reference function $h(\overline{X})$ is aligned. $\overline{X}$ and $\bar{f}_X$ are two-dimensional vectors for Cartesian coordinates at the input and the filter planes, respectively. At the output plane the correlation response is obtained.

In Fig. 2 a block diagram of the encoding procedure (both for input and filter reference patterns) is given.

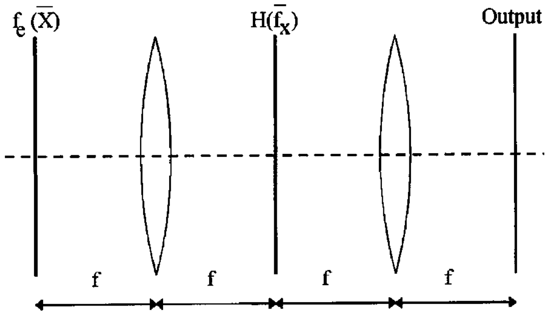

Fig. 1. Conventional VanderLugt correlation scheme that was used for performing color pattern recognition.

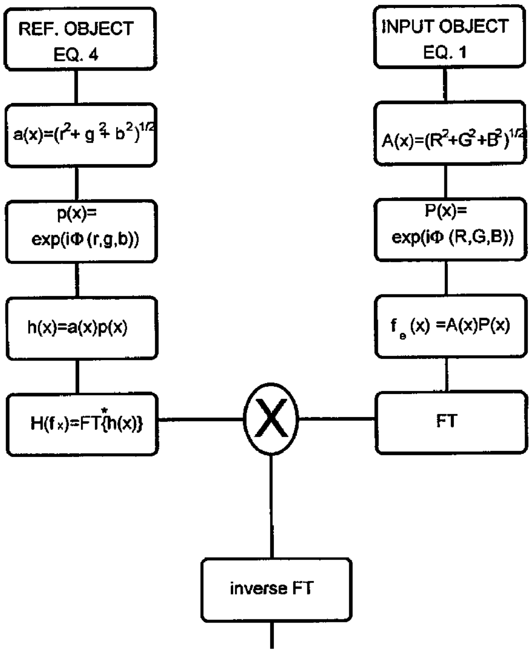

Fig. 2. Block diagram of the encoding procedure. FT's, Fourier transforms.

In our notation the input color target $\bar{f}(\overline{X})$ is a three-dimensional vector owing to its RGB decomposition:

$$\bar{f}(\overline{X}) = R(\overline{X})\hat{R} + G(\overline{X})\hat{G} + B(\overline{X})\hat{B}, \tag{1}$$

where $R(\overline{X})$ contains the red color component, $G(\overline{X})$ the green, and $B(\overline{X})$ the blue. We assume that the three unit vectors $\hat{R}, \hat{G}, \hat{B}$ are orthonormal. The next step is the calculation of the total input amplitude of the object:

$$\begin{aligned} A(\overline{X}) &= [\bar{f}(\overline{X}), \bar{f}(\overline{X})]^{1/2} \\ &= [R^2(\overline{X}) + G^2(\overline{X}) + B^2(\overline{X})]^{1/2}. \end{aligned} \tag{2}$$

Now the phase code of the color information is obtained based on a preprepared lookup table (LUT) that converts each possible color to a certain phase value. This LUT, denoted by $\Phi(R, G, B)$, should take into account all various color combinations. It depends on the color histogram of the object itself, as the following examples show. Section 3 discusses in more detail the design of the LUT.

The input encoded pattern is then

$$f_e(\overline{X}) = A(\overline{X})\exp\{i\Phi[R(\overline{X}), G(\overline{X}), B(\overline{X})]\}. \tag{3}$$

A similar process is used for encoding the filter reference function. Here the starting function is the reference object $\overline{\mathrm{ref}}(\overline{X})$, which again is decomposed into the three basic colors:

$$\overline{\mathrm{ref}}(\overline{X}) = r(\overline{X})\hat{R} + g(\overline{X})\hat{G} + b(\overline{X})\hat{B}. \tag{4}$$

Then the same procedure as used in Eq. (2) and (3) with the same LUT is performed in order to find the

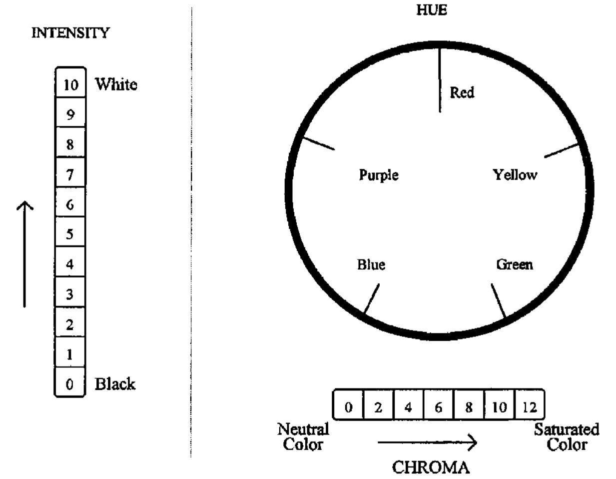

Fig. 3. Hue, intensity, and chroma representation on the Munsell system.

encoded reference pattern $h(\bar{X})$ (see Fig. 2). For implementing the matched filter, $h(\bar{X})$ has to be Fourier transformed. The result is $H(f_x)$, a complex amplitude function that should be encoded as a computer-generated hologram.

Figure 2 summarizes schematically the optical processing procedure. It is a conventional correlation between the input encoded pattern $f_e(\bar{X})$ and the encoded reference pattern $h(\bar{X})$. We claim that the obtained output correlation peak has at least the same quality as that obtained by the multichannel systems. This argument is demonstrated in Section 4 with computer simulations.

Practically, the presentation of $f_e(\bar{X})$ at the input plane of Fig. 1 could be done with two SLM's. A compact way is to place two liquid-crystal television panels in contact, one working in amplitude-modulation mode and the other in phase mode. A significant simplification of the system would be achieved if the input object were a pure amplitude or a pure phase function. Fortunately, we considered that, for many cases, good results could be obtained by use of only the phase modulator without the amplitude one. This means that the input encoded pattern is now

$$f_e(\bar{X}) = \exp\{i\Phi[R(\bar{X}), G(\bar{X}), B(\bar{X})]\}. \tag{5}$$

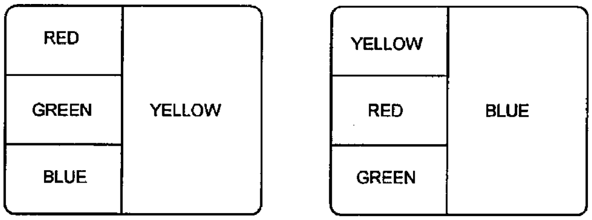

Fig. 5. Example of two color objects that provide the same correlation peak according to the Fig. 4 code.

It must be considered that commercially available SLM's always introduce a residual amplitude modulation, a pure phase-only modulation not being possible. In addition to the simplicity advantage, the use of such a phase-only encoding procedure practically provides less-noisy correlation outputs because each SLM adds some noise to the total result. Simulations that use several codifications of color images are presented in Section 4. The need for the amplitude information of the color code of the input and the reference objects is also examined.

3. Color Code

The LUT color-encoding procedure could be done in many ways. Our approach offers only two degrees of freedom, the phase and the amplitude. The codification that we used is inspired by the Munsell color system. In this system, hue, intensity, and chroma are coordinates of a color space. The Munsell color system is based on the idea of a color solid system; it is a color atlas whose purpose is to assist the color user in describing, selecting, and matching colors to place them on a three-dimensional space. Figure 3 shows a horizontal section of the color solid. The vertical axis, shown on the left part of the figure, represents the loci of the neutral colors. The intensity is ar-

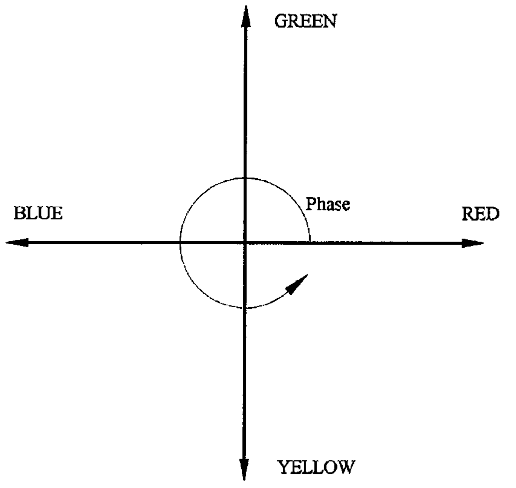

Fig. 4. Example of color–phase code for four colors.

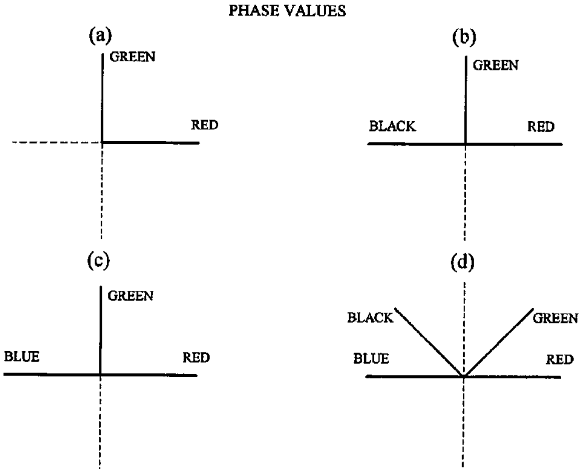

Fig. 6. Various examples of partial-phase-plane color codes.

ranged on this axis, with black at the bottom and white at the top. The distance of a sample color from the vertical axis is governed by the saturation, called chroma in the Munsell system. Finally, the hue is expressed as an angle between 0° and 360°. In Fig. 3 some colors with their correspondent hue values are represented.

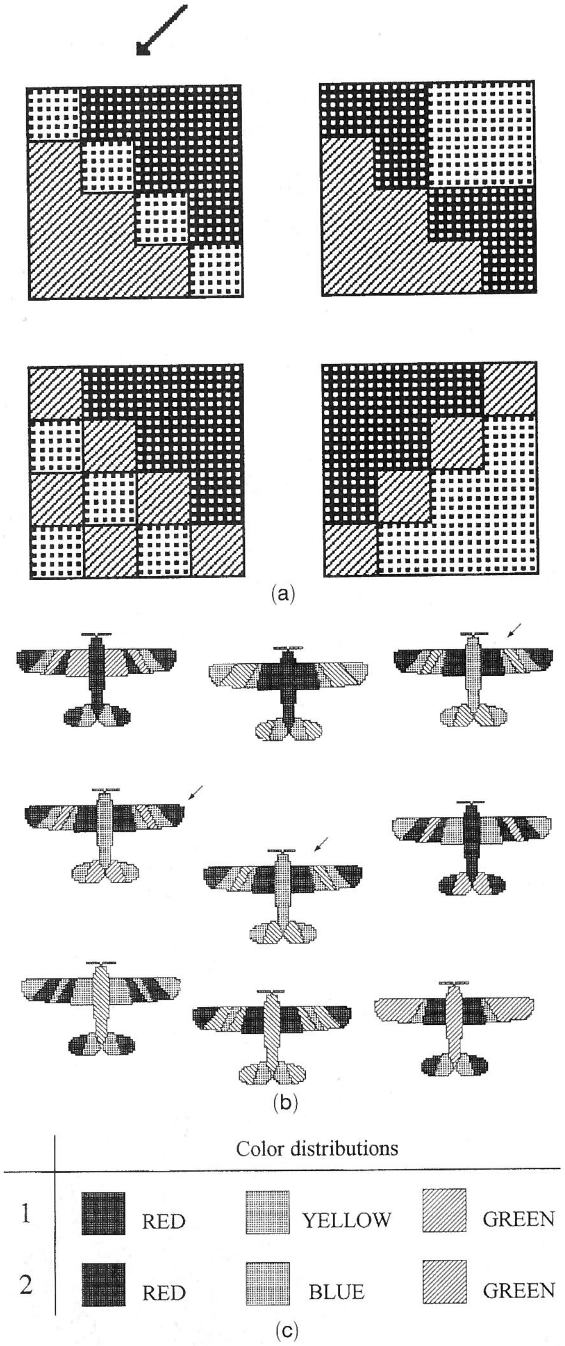

Fig. 7. Input planes for the various simulations: (a) the square family plane, (b) the airplane family, (c) and the two different color distributions, in which 1 denotes the two main colors (red and green) and 2 denotes the three main colors (red, green, and blue). In (a) and (b), the reference targets are marked with arrows.

Table 1. Normalized Correlation-Peak-Value Simulation Results with Fig. 7(a) as the Input-Plane and Color Combination 1 in Fig. 7(c) (Two-Color Example)

Input	Filter Reference	Auto-correlation	Highest Cross Correlation
Phase and amplitude	Phase and amplitude	1.00	0.24
Phase only	Phase and amplitude	1.00	0.41
Phase only	Phase only	1.00	0.71
Amplitude only	Amplitude only	1.00	1.00
Multichannel		1.00	0.55

In our codifications the angle associates with the hue is translated into a phase value. The intensity is addressed in our model by the amplitude modulator. The chroma is neglected in the suggested model. Such a simplification of the Munsell color system is common also in color-television technology, as is described briefly in Ref. 21.

Motivated by Munsell's model, in Fig. 4, we give an example of such a color LUT code. All of the expected colors are distributed uniformly among the different angles. The angle of each color vector is then translated to a phase value. For color-pattern-recognition application, this color code provides exactly the same correlation peak if the color distribution is rotated around the origin of the Fig. 4 coordinate system. Figure 5 shows such an example. The color-encoded correlator provides the same correlation peaks with the two objects of Fig. 5 and uses the LUT shown in Fig. 4. Although a phase shift of 90° is obtained between the two correlation peaks, a conventional intensity detection system at the output plane cannot detect it. Another drawback of the color-code LUT of Fig. 4 is that a common liquid-crystal television panel cannot provide a full 360° phase-modulation depth. The above two problems can be overcome with a phase interval smaller than 360°. Thus a cyclic change of all the colors in the image does not correspond to a global phase shift. Some examples of color codes that fulfill these conditions are shown in Fig. 6, in which the different phase vectors of Fig. 4 are rearranged. By use of these LUTs, the correlator provides a correlation peak only for a single color combination of the input object.

Table 2. Normalized Correlation-Peak-Value Simulation Results with Fig. 7(a) as the Input-Plane and Color Combination 2 in Fig. 7(c) (Three-Color Example)

Input	Filter Reference	Auto-correlation	Highest Cross Correlation
Phase and amplitude	Phase and amplitude	1.00	0.38
Phase only	Phase and amplitude	1.00	0.39
Phase only	Phase only	1.00	0.50
Amplitude only	Amplitude only	1.00	1.00

Table 3. Normalized Correlation-Peak-Value Simulation Results with Fig. 7(b) as the Input-Plane and Color Combination 1 in Fig. 7(c) (Two-Color Example)

Input	Filter Reference	Auto-correlation	Highest Cross Correlation
Phase and amplitude	Phase and amplitude	1.00	0.20
Phase only	Phase and amplitude	1.00	0.47
Phase only	Phase only	1.00	0.63
Amplitude only	Amplitude only	1.00	1.00
Multichannel		1.00	0.55

Table 4. Normalized Correlation-Peak-Value Simulation Results with Fig. 7(b) as the Input-Plane and Color Combination 2 in Fig. 7(c) (Three-Color Example)

Input	Filter Reference	Auto-correlation	Highest Cross Correlation
Phase and amplitude	Phase and amplitude	1.00	0.36
Phase only	Phase and amplitude	1.00	0.46
Phase only	Phase only	1.00	0.55
Amplitude only	Amplitude only	1.00	1.00

In Figs. 6(b) and 6(d) the black color is encoded in order to perform phase-only codification. In these cases the black color is considered as a regular color.

In summary, the design of the LUT depends on several parameters, such as the available SLM devices and the color combinations that should cause recognition and rejection.

4. Computer-Simulation Results

In this section, computer simulations of the suggested color-encoding system are shown in order to demonstrate the performance of this system. Two families of objects are used, squares [Fig. 7(a)] and airplanes [Fig. 7(b)]. In addition, every input family is used with two different color combinations: first, with two main colors [color map 1 in Fig. 7(c)], and second, with three main colors [color map 2 in Fig. 7(c)]. The two colors examples are given for the sake of comparison with previous multichannel system performance,[10,11] in which the study was carried out with two channels [map 1, Fig. 7(c)]. The yellow color was displayed as a combination of red and green. In our code we do the same according to the Fig. 6(a) code, in which we assign a phase of 45° for the yellow color.

Tables 1–4 give the simulation results. Four cases are considered for encoding of the input plane and the filter reference object: (1) encoding with phase and amplitude, (2) encoding of the input plane with phase-only code, (3) encoding of both the input plane and the filter reference with phase-only code, and (4) encoding of both with amplitude-only code. The results are given in normalized values so the value of the autocorrelation peak is always 1. In the right columns the information about the discrimination

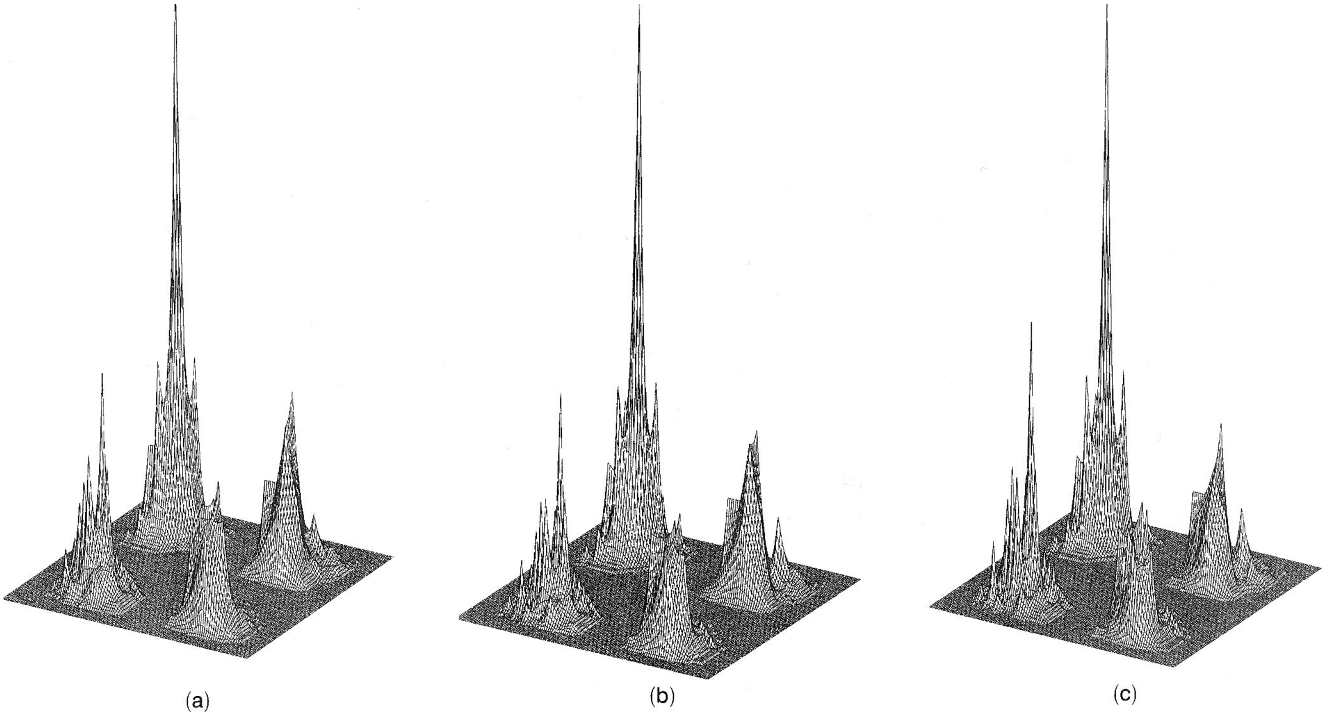

Fig. 8. Three-dimensional illustrations of the obtained correlation output computer simulations of Table 2: (a) when the object and the filter reference are phase and amplitude encoded, (b) the same as (a) but when the object is phase-only encoded, and (c) when the object and the filter reference are phase-only encoded.

capability of the system is given by values of the highest cross-correlation peaks normalized to the relevant autocorrelation-peak values.

Table 1 shows the results for Fig. 7(a) as the input-plane and color combination 1 in Fig. 7(c) as the color map. As the phase code, we used Figs. 6(a) and (b) for both the input and the filter reference plane. In the case of phase-only code (without amplitude), Fig. 6(b) is used to allow a special code to be used also for the black areas. The multichannel simulations that were calculated in Ref. 10 are given in the last row. Even with a phase-only input plane encoding (second row), the obtained results are significantly better than the multichannel performance. Table 2 shows the same but with Fig. 7(a) and color combination 2 in Fig. 7(c) as the input plane and the color map, respectively, and the phase code shown in Figs. 6(c) and (d). Tables 3 and 4 are the same as Tables 1 and 2 but with Fig. 7(b) as the input image (with the relevant color maps). Also in this last case, the superiority of the suggested method is demonstrated, and one can notice that a phase-only code for the input plane is sufficient for excellent performance.

As an illustration of details regarding the shape of the correlation peak, the output planes of Table 2 are plotted. Figures 8(a), 8(b), and 8(c) show the output correlation planes for the first three rows of Table 2. For practical uses the simulations indicate that the suggested color-encoding system provides better results than those obtained with multichannel systems. It is obvious that the amplitude modulation of the input encoded plane is not necessary. However, the use of amplitude- and phase-encoded reference objects provides better performance, fortunately, without any addition efforts (the input plane is still phase only).

5. Conclusions

In conclusion, a novel approach for performing colored-image detection is introduced. While most of the other color-pattern-recognition approaches are based on multichannel configurations, here the optical system is a single-channel one. This leads to a very compact and simple correlator. The colors are encoded as a phase distribution according to a precalculated lookup table. Several considerations for designing the lookup table are inspired by the Munsell color system. Practically, a liquid-crystal television panel, working in a phase mode, is suggested for presenting the input phase code. In addition, another amplitude-only spatial light modulator can be placed at the input plane in order to present the total intensity distribution of the input object. For greater simplicity, we suggest removal of the amplitude modulator to make the final system less complicated than a conventional VanderLugt correlator. Computer simulations show that, even with the phase-only code, in comparison with the multichannel system, better performance is obtained by the single-channel system.

Further investigation can be done by the use of many of the well-known advanced optical correlation techniques, such as the phase-only filter, trade-off filters, and invariant pattern recognition.

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