Color image recognition by use of a joint transform correlator of three liquid-crystal televisions

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We present a joint transform correlator for color image recognition by using three liquid-crystal spatial light modulators. A method for simultaneously obtaining the correlation peaks of red, green, and blue is proposed and experimentally demonstrated. © 2002 Optical Society of America

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1. Introduction

Use of the joint transform correlator (JTC) is one of two common techniques used for optical image recognition.[1–3] In this technique, liquid-crystal-television (LCTV)-based JTC systems have been widely used for monochromatic signal detection and identification.[4] In practice, many visual signals are colored. Both the shapes and the colors of the input patterns are essential characteristics for pattern recognition. Thus extending the capability of the optical pattern recognition system for color-image inputs is a very attractive task. In fact, color pattern recognition systems that use matched filters[5–8] and JTCs[9–11] have been demonstrated. In those systems, either three lasers with different colors are used or an additional grating device is used to separate the three original-color [red-green-blue (RGB)] components of a composite input image. In both cases, the systems are complicated. In recent years there has been a rapid development in display technology. High-resolution LCTV projectors that contain three panels, one panel displaying one of the three original colors of the input image, are commercially available. In these devices, separation of the RGB components of a composite image is automatically performed by the built-in circuit board. The color separation and displaying characteristics of the LCTV projectors provide a good application for color image recognition.

In this paper a three-channel JTC structure for performing color pattern recognition is presented. In the system, each channel is a JTC correlator responsible for the recognition of a specific color component (RGB) of the color image. The selection of suitable focal lengths of the lenses of the joint-transformed correlators of RGB color components allows the correlation peaks for RGB components to be displayed simultaneously at separate locations on a screen, and the color image recognition can be achieved. In the following section, the principle of our system will first be described. Then Section 3 presents the system parameters and experimental results. Section 4 gives some conclusions.

2. Principle

In our system, three liquid-crystal display (LCD) panels of a LCTV projector are used as the input devices, each panel displaying a different color component of the input image. The colors of the input pattern are separated into RGB colors by the driver circuits of the LCTV projector. If each LCD panel is put at the front focal plane of a Fourier lens, then the Fourier spectrum of each color can be obtained at the back focal plane. Owing to the pixelated structure of the LCD device, each Fourier spectrum has multiple diffraction orders. One way to separate the Fourier spectra of color images is to choose different orders of different colors. Then the Fourier spectra of RGB components will be spatially separated. But the correlation peaks for three different colors will appear at the same position on the correlation plane when the focal lengths for different colors are the same. Another way of achieving this is to choose the same diffraction order but with

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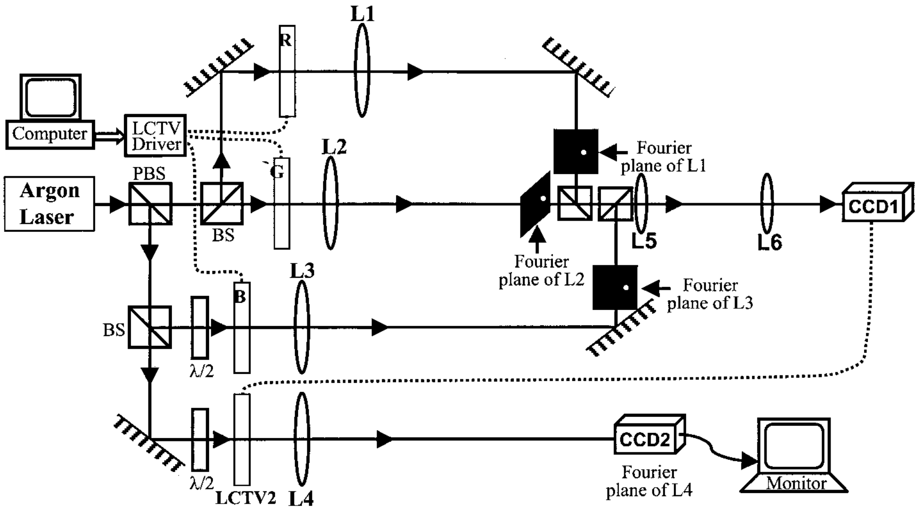

Fig. 1. Color pattern recognition in a joint transform correlator system.

different focal lengths for different colors. In this paper we use the second method.

Figure 1 shows our system of the joint transform correlator. The RGB components of input objects and the reference images are jointly displayed on three LCTV panels. Consider a reference image $g(x, y)$ and an object image $h(x, y)$, both of which are color images. The RGB components of the images are separated by the driver circuit of the projector and are displayed on the three corresponding LCTV panels. The total inputs of the three panels can be written as

$$
\begin{aligned}
f_{\mathrm{in}}(x, y) &= f_r(x, y) + f_g(x, y) + f_b(x, y) \\
&= \left[g_r\left(x - \frac{d}{2}, y \right) + h_r\left(x + \frac{d}{2}, y \right) \right] t_r(x, y) \\
&\quad + \left[g_g\left(x - \frac{d}{2}, y \right) + h_g\left(x + \frac{d}{2}, y \right) \right] t_g(x, y) \\
&\quad + \left[g_b\left(x - \frac{d}{2}, y \right) + h_b\left(x + \frac{d}{2}, y \right) \right] t_b(x, y),
\end{aligned}
\tag{1}
$$

where f_r, f_g, and f_b represent the patterns that are displayed on the red, green, and blue LCTV, respectively. $t(x, y)$ represents the amplitude transmittance of the LCTV panel, and d represents the spatial separation between the reference and the object image on the LCD panel. As Fig. 1 shows, each pair of the R, G, B inputs are jointly transformed by lenses L1, L2, and L3, respectively. The summation of the three Fourier spectra can be found to be

$$
\begin{aligned}
F(\xi, \eta) &= \left[G_r(\xi, \eta) \exp\left(-i \frac{2\pi}{\lambda l_r} \frac{d}{2} \xi \right) + H_r(\xi, \eta) \exp\left(i \frac{2\pi}{\lambda l_r} \frac{d}{2} \xi \right) \right] \otimes T_r(\xi, \eta) \\
&\quad + \left[G_g(\xi, \eta) \exp\left(-i \frac{2\pi}{\lambda l_g} \frac{d}{2} \xi \right) + H_g(\xi, \eta) \exp\left(i \frac{2\pi}{\lambda l_g} \frac{d}{2} \xi \right) \right] \otimes T_g(\xi, \eta) \\
&\quad + \left[G_b(\xi, \eta) \exp\left(-i \frac{2\pi}{\lambda l_b} \frac{d}{2} \xi \right) + H_b(\xi, \eta) \exp\left(i \frac{2\pi}{\lambda l_b} \frac{d}{2} \xi \right) \right] \otimes T_b(\xi, \eta),
\end{aligned}
\tag{2}
$$

where $\otimes$ represents convolution operation; ξ and η are the coordinates at the Fourier plane; G and H are the Fourier transforms of the patterns $g(x, y)$ and $h(x, y)$; l_r, l_g, and l_b are the focal lengths of L1, L2, and L3; and T_r, T_g, and T_b are the Fourier transforms of the amplitude transmittance of the red, green, and blue LCTV panels, respectively. Because the LCTV panel is pixelated, its Fourier spectra has multiple diffraction orders and thus T_r, T_g, and T_b can be written as a summation of replica of Fourier spectra,

$$
\begin{aligned}
T_i(\xi, \eta) &= \sum_m \sum_n A_{mn} \delta(\xi + m\xi_i, \eta + n\eta_i), \\
i &= r, g, b, \qquad m = 0, \pm 1, \pm 2, \ldots, \\
n &= 0, \pm 1, \pm 2, \ldots,
\end{aligned}
\tag{3}
$$

where A_{mn} is the diffracted amplitude of the mn order and $A_{mn} = \mathrm{sinc}(mD\xi_i)\mathrm{sinc}(nD\eta_i)$ and D is the pixel size of the LCTV panels. If we put an aperture at the Fourier plane such that only one diffraction order passes through, then spatial filtering can be achieved. For example, if we choose the first order ($m = 1, n = 0$) of the Fourier spectra, then the joint-transformed spectra in Eq. (2) can be rewritten as

$$\begin{aligned} F_1(\xi,\eta) = {} & c_1\left\{G_r(\xi-\xi_r,\eta)\exp\left[-i\frac{2\pi}{\lambda l_r}\frac{d}{2}(\xi-\xi_r)\right]\right. \\ & \left.+ H_r(\xi-\xi_r,\eta)\exp\left[i\frac{2\pi}{\lambda l_r}\frac{d}{2}(\xi-\xi_r)\right]\right\} \\ & + c_2\left\{G_g(\xi-\xi_g,\eta)\exp\left[-i\frac{2\pi}{\lambda l_g}\frac{d}{2}(\xi-\xi_g)\right]\right. \\ & \left.+ H_g(\xi-\xi_g,\eta)\exp\left[i\frac{2\pi}{\lambda l_g}\frac{d}{2}(\xi-\xi_g)\right]\right\} \\ & + c_3\left\{G_b(\xi-\xi_b,\eta)\exp\left[-i\frac{2\pi}{\lambda l_b}\frac{d}{2}(\xi-\xi_b)\right]\right. \\ & \left.+ H_b(\xi-\xi_b,\eta)\exp\left[i\frac{2\pi}{\lambda l_b}\frac{d}{2}(\xi-\xi_b)\right]\right\}, \end{aligned} \tag{4}$$

where c_1, c_2, and c_3 are the amplitudes of the first-order diffraction for the red, green, and blue channels, respectively. Note that the three terms in Eq. (4) possess the same spatial orientation on the Fourier planes. But because we choose different focus lengths of the Fourier lenses for the three LCTV, i.e., $l_r \neq l_g \neq l_b$, then the centers of the three Fourier spectra are located at three positions, ξ_r, ξ_g, and ξ_b. These Fourier spectra are recombined by beam splitters BS1 and BS2 and are imaged into camera CCD1 by lenses L5 and L6. CCD1 detects the power spectra of the joint transform, which can be written as

$$\begin{aligned} |F_1(\xi,\eta)|^2 = {} & C_1\left\{|G_r(\xi-\xi_r,\eta)|^2 + |H_r(\xi-\xi_r,\eta)|^2\right. \\ & + G_r(\xi-\xi_r,\eta) \\ & \times H_r^*(\xi-\xi_r,\eta)\exp\left[-i\frac{2\pi}{\lambda l_r}d(\xi-\xi_r)\right] \\ & \left.+ \text{c.c.}\right\} + C_2\left\{|G_g(\xi-\xi_g,\eta)|^2\right. \\ & + |H_g(\xi-\xi_g,\eta)|^2 + G_g(\xi-\xi_g,\eta) \\ & \times H_g^*(\xi-\xi_g,\eta)\exp\left[-i\frac{2\pi}{\lambda l_g}d(\xi-\xi_g)\right] \\ & \left.+ \text{c.c.}\right\} + C_3\left\{|G_b(\xi-\xi_b,\eta)|^2\right. \\ & + |H_b(\xi-\xi_b,\eta)|^2 + G_b(\xi-\xi_b,\eta) \\ & \times H_b^*(\xi-\xi_b,\eta)\exp\left[-i\frac{2\pi}{\lambda l_b}d(\xi-\xi_b)\right] \\ & \left.+ \text{c.c.}\right\}, \end{aligned} \tag{5}$$

where C_1, C_2, and C_3 are the intensities for the red, green, and blue spectra, respectively, and * and c.c. represent the complex conjugate. Note from Eq. (5) that the grating period of the power spectra for red, green, and blue are $\lambda l_r/d$, $\lambda l_g/d$, and $\lambda l_b/d$, respectively. The power spectra detected by CCD1 is displayed on LCTV2, and then it is Fourier transformed by lens L4. The output intensity is detected by CCD2, which can be written as

$$\begin{aligned} I_{\text{output}} = {} & |\Im^{-1}\{|F_1(\xi,\eta)|^2\}|^2 \\ = {} & |C_1(g_r \star g_r + h_r \star h_r) + C_2(g_g \star g_g \\ & + h_g \star h_g) + C_3(g_b \star g_b + h_b \star h_b)|^2 \\ & + \left|C_1\left[(g_r \star h_r)\otimes\delta\left(x' - \frac{l}{l_r}d\right)\right]\right. \\ & + C_2\left[(g_g \star h_g)\otimes\delta\left(x' - \frac{l}{l_g}d\right)\right] \\ & \left.+ C_3\left[(g_b \star h_b)\otimes\delta\left(x' - \frac{l}{l_b}d\right)\right]\right|^2 \\ & + \left|C_1\left[(g_r \star h_r)\otimes\delta\left(x' + \frac{l}{l_r}d\right)\right]\right. \\ & + C_2\left[(g_g \star h_g)\otimes\delta\left(x' + \frac{l}{l_g}d\right)\right] \\ & \left.+ C_3\left[(g_b \star h_b)\otimes\delta\left(x' + \frac{l}{l_b}d\right)\right]\right|^2, \end{aligned} \tag{6}$$

where $\star$ represents the correlation operation and l is the focal length of lens L4. In Eq. (6), it is seen that the autocorrelation terms of the input and the reference images are overlap and are located at the center of the output plane and that the cross-correlation peaks for red, green, and blue patterns are spatially separated at six positions, $\pm(l/l_r)d$, $\pm(l/l_g)d$, and $\pm(l/l_b)d$, respectively. If the input pattern $g(x, y)$ is identical with the reference image $h(x, y)$ both in shapes and colors, then six correlation peaks will appear on the output plane. If $g(x, y)$ and $h(x, y)$ are identical in shapes and both are red, then there will be only two correlation peaks appearing at the locations $\pm(l/l_r)d$. However, if the two patterns are identical in shapes but are different colors, e.g., one is red and the other one is green, then there should be no correlation peak on the output plane.

3. Experimental Results

In our experiment the focal lengths of the lenses for red, green, and blue signals are 60, 84.1, and 40 cm, respectively. The focal length of lens L4 is 60 cm. The focal lengths of lens L5 and L6 are identical and are equal to 20 cm.

Figure 2 shows the input and the reference patterns; both are the white characters A. The separation between the two characters is 0.4 cm on the LCD screen. Therefore the grating periods of the power spectra corresponding to red, green, and blue are 77.1, 108.1, and 51.4 μm, respectively. The pixel size of CCD1 is 11 μm × 13 μm. Thus the joint transform power spectra are detectable by CCD1. The first-order power spectra of the three colors are

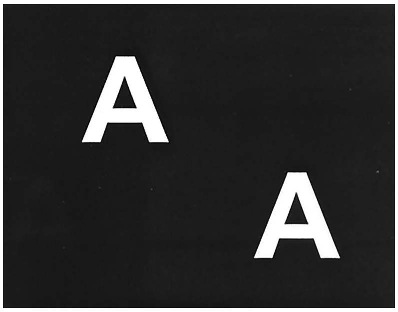

Fig. 2. Original input patterns.

selected by apertures with a diameter of 1 mm and are imaged onto CCD1 by lenses L5 and L6. The detected power spectra is shown in Fig. 3. It can be seen that the power spectra of the three colors are separated and located at three different positions in the Fourier plane. It can also be seen that the top spectra is strongest and the bottom spectra is the weakest because the input image has a large amount of green and a small amount of blue.

The detected power spectra is displayed on LCTV2 and is Fourier transformed by L4. The correlation output signal is detected by CCD2 and is shown in Fig. 4. It is seen that there are six cross-correlation peaks produced by the identical white patterns. The central bright spot is the autocorrelation peak. The two points nearest to the central peak represent the correlation outputs for the blue color of the input patterns. The next two points represent the correlation outputs for red. And the two points farthest from the central peak represent the correlation outputs for green. With the experimental parameters, the distances between the central peak and the correlation peaks for red, green, and blue are 0.4, 0.6, and 0.29 cm, respectively.

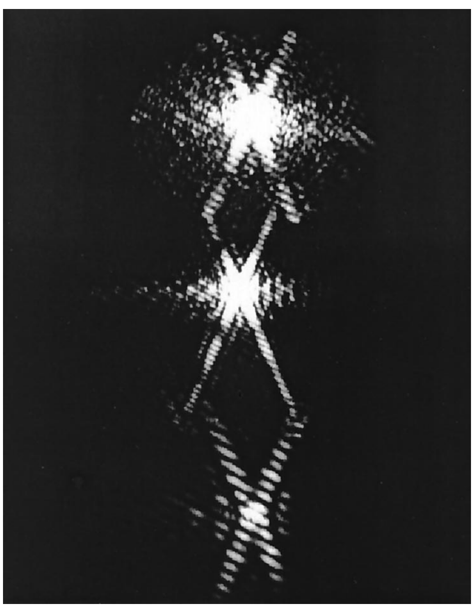

Fig. 3. Power spectra of two white input patterns.

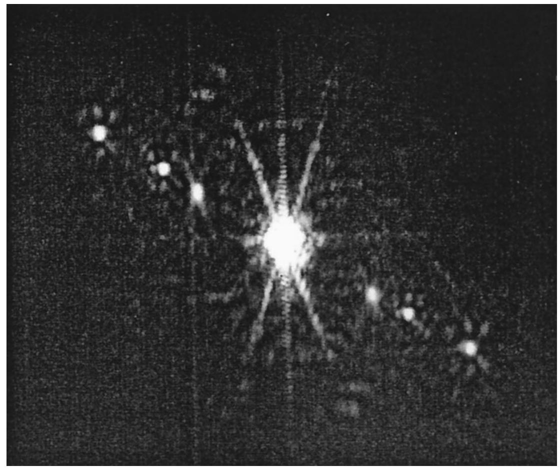

Fig. 4. Correlation output for two white patterns of Fig. 2.

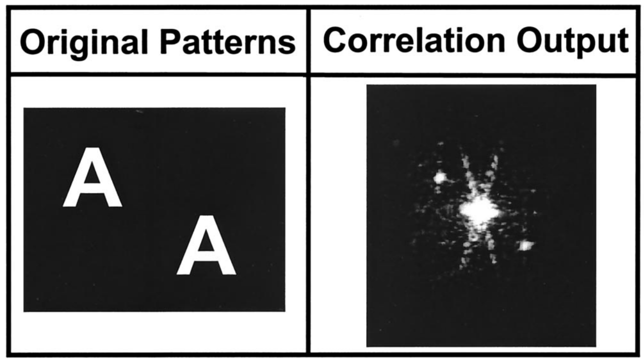

Fig. 5. Correlation output for white and blue patterns. The left image shows the input pattern of letters A's in different colors. The upper A is blue, and the lower A is white. The right image shows the correlation output.

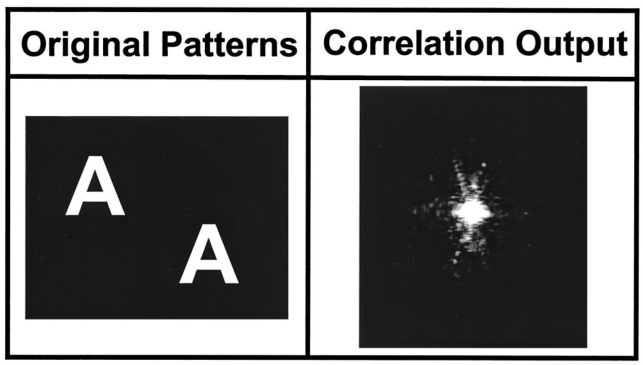

Fig. 6. Correlation output for red and blue input patterns. The upper A is red, and the lower A is blue. The right image shows the correlation output.

The correlation result of changing the input characters to blue while the reference image is kept white is shown in Fig. 5. It can be seen that only two correlation peaks for blue have been observed. The relative values of the correlation peaks for red, green, and blue are 36, 56, and 255, respectively. Next, the correlation output of changing the color of the input character to red and the reference character to blue is shown in Fig. 6. It can be seen that there is no correlation peak in the correlation plane.

4. Conclusion

In this paper we have proposed and experimentally demonstrated a joint transform correlation system for color image recognition. The system utilizes three LCD panels to display RGB components of a color image. When different focal lengths for Fourier lenses of the RGB images are chosen, the correlation peaks of the three color components are spatially separated and located at different positions. By detection of the correlation outputs, color image recognition has been achieved.

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