Color pattern recognition based on the joint fractional Fourier transform correlator

Weimin Jin (金伟民) and Yupei Zhang (张玉佩)

Institute of Information Optics, Zhejiang Normal University, Jinhua 321004

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A new system of multi-channel single-output joint fractional Fourier transform correlator (JFRTC) for color pattern recognition is proposed based on the conventional system of multi-channel single-output joint transform correlator (JTC). The theoretical analysis and optical experiments are performed. With this method, one can obtain three correlation peaks at the output plane which show a pair of desired cross-correlation peaks and one auto-correlation peak. In comparison, the conventional system leads to more correlation peaks playing a noise role in color pattern recognition.

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Optical correlator is mainly investigated in optical pattern recognition. It mainly consists of two types. One is Vander Lugt correlator (VLC) based on matched filter[1]; the other is joint transform correlator (JTC)[2]. JTC can process in real time without making filters and precise alignment, so it becomes the hot topic in pattern recognition[3,4]. Fractional Fourier transform (FRT) has been used extensively in the field of optical information processing with the development in recent years[5]. After fractional correlation (FC) had been introduced[6], joint fractional Fourier transform correlator (JFRTC) was put forward using FRT to replace Fourier transform (FT)[7]. Compared with JTC, JFRTC has more advantages[8−10].

The aforementioned correlators are fit for monochromatic pattern recognition. In fact, most images are chromatic, and color is the most important and basic factor of image information. So it is practical to investigate the color pattern recognition. There have been some papers studying color pattern recognition[11−14] based on optical correlation method. Although most of the JTCs adopt monochromatic input images for recognition, the utilization of multi-channel input images may provide additional correlation functions to be performed. Deutsch *et al.* developed a multi-channel single-output JTC by rearrangement of all channel images at the input plane[15], which is the most popular way in color pattern recognition. However, this method generates large zero-order term that results in poor detection performance. So Wu *et al.* proposed a distortion-invariant multi-channel single-output JTC based on the RGB (red, green, and blue) color space[16]. Not only can the zero-order term be eliminated, but also distortion invariance is achieved. Recently, Chen *et al.* proposed the multi-channel nonzero-order JTC based on the HSV (hue, saturation, and value) color space[17]. The HSV multi-channel separation yields better results compared with alternate RGB separation by producing sharper correlation peak intensity. Recognition is clearly improved.

The method of Deutsch *et al.*[15] is based on JTC, by which one can obtain 36 correlation expressions, forming 15 locations of correlation peaks at the output plane. There is only one pair of correlation peaks that is useful and the others become noise, especially in multi-target recognition. For this problem, we propose a new system of multi-channel single-output JFRTC for color pattern recognition, which makes the best of the shift-variant property of FRT and combines with the multi-channel single-output method. we obtain the result of 12 correlation expressions which form three locations of correlation peaks at the output plane, as is the same case in the single-channel JTC system.

The FRT of image $g(x,y)$ with the order of p is defined as

$$G(\xi,\eta)=\iint\limits_{-\infty}^{\infty} g_{(x,y)}\exp\left\{j\pi\frac{x^2+y^2+\xi^2+\eta^2}{\tan\varphi}\right.$$
$$\left.-j2\pi\frac{x\xi+y\eta}{\sin\varphi}\right\}\mathrm{d}x\mathrm{d}y. \tag{1}$$

Supposing that $r(x,y)$ is the color reference image and $t(x,y)$ is the color target image, based on the tricolor principle, the reference image can be separated into three components of $r_{\mathrm{R}}(x,y)$, $r_{\mathrm{G}}(x,y)$, $r_{\mathrm{B}}(x,y)$ and the target image can be separated into three components of $t_{\mathrm{R}}(x,y)$, $t_{\mathrm{G}}(x,y)$, $t_{\mathrm{B}}(x,y)$. At the input plane of JFRTC, the image can be expressed as

$$f(x,y)=\sum_{i=1}^{3}\left[r_i(x-x_0,y-y_i)+t_i(x+x_0,y-y_i)\right], \tag{2}$$

where x_0 is the translation quantity between the reference and target images at x axis; and $i=1,2,3$ respectively denote red, green, and blue images, which can be written as $r_1=r_{\mathrm{R}}$, $r_2=r_{\mathrm{G}}$, $r_3=r_{\mathrm{B}}$, $t_1=t_{\mathrm{R}}$, $t_2=t_{\mathrm{G}}$, $t_3=t_{\mathrm{B}}$; y_1, y_2, y_3 respectively denote the corresponding distances between red, green, and blue image at y axis, as shown in Fig. 1, where $y_1=y_0$, $y_2=0$, $y_3=-y_0$. In order to realize the JFRTC, one can perform optical experiments in double-light-path system[9]. Supposing that there is an angle θ between two light paths, the reference light beam will plus a phase modulation $\exp(j\pi p_0 x)$ relative to the target light beam, where $p_0=\frac{2\sin\theta}{\lambda}$. Equation (2) is changed as

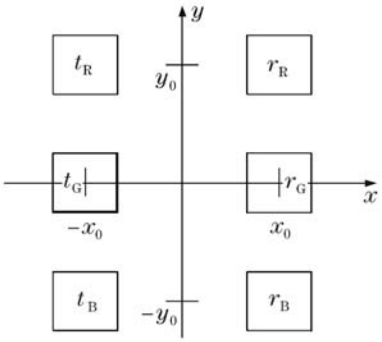

Fig. 1. Arrangement of six gray-scale images from the red, green, and blue components of the reference and test images at the input plane.

$$f(x,y)=\sum_{i=1}^{3}\left[r_i\left(x-x_0,y-y_i\right)\exp\left(j\pi p_0 x\right)+t_i\left(x+x_0,y-y_i\right)\right]. \tag{3}$$

Performing FRT with the order of p, we gain fractional spectra expressed as

$$\begin{aligned}F^p\{f(x,y)\}&=F(\xi,\eta)\\&=F^p\Big\{\sum_{i=1}^{3}[r_i(x-x_0,y-y_i)\exp(j\pi p_0 x)+t_i(x+x_0,y-y_i)]\Big\}\\&=\sum_{i=1}^{3}\Big\{\exp\{-j\pi[x_0\sin\varphi(\xi-x_0\cos\varphi)+y_i\sin\varphi(\eta-y_i\cos\varphi)]\}\\&\quad\times\exp[j\pi p_0(\xi-\frac{p_0}{4}\sin\varphi)]\\&\quad\times R_i(\xi,\eta)_{(\xi-x_0\cos\varphi-\frac{p_0}{2}\sin\varphi,\eta-y_i\cos\varphi)}\\&\quad+\exp\{-j\pi[-x_0\sin\varphi(\xi+x_0\cos\varphi)+y_i\sin\varphi(\eta-y_i\cos\varphi)]\}\\&\quad\times T_i(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}\Big\},\end{aligned} \tag{4}$$

where $R_i(\xi,\eta)=F^p\{r_i(x,y)\}$, $T_i(\xi,\eta)=F^p\{t_i(x,y)\}$.

Suppose R_R, R_G, R_B, T_R, T_G, T_B respectively denote the corresponding fractional spectra of r_R, r_G, r_B, t_R, t_G, t_B. On the one hand, the fractional spectra of three channels can be separated at the frequency plane due to the shift-variant property of FRT, that is to say, R_R, R_G, R_B are absolutely separated and T_R, T_G, T_B are absolutely separated. On the other hand, R_R and T_R, R_G and T_G, R_B and T_B can completely overlapped at the frequency plane owing to the double-light-path system[9]. In order to achieve these two points, it requires

$$p_0=-4x_0\cot\varphi. \tag{5}$$

The fractional spectra can be written as

$$F^p\{f(x,y)\}=\sum_{i=1}^{3}\{CR_i(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}+C'T_i(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}\}. \tag{6}$$

And the joint power spectra recorded by charge copule device (CCD) can be expressed as

$$\begin{aligned}\left|F^p\{f(x,y)\}\right|^2&=\Big|\sum_{i=1}^{3}\{CR_i(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}+C'T_i(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}\}\Big|^2\\&=o_1+o_2+o_3,\end{aligned} \tag{7}$$

$$o_1=\sum_{i=1}^{3}\Big[\left|R_i(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}\right|^2+\left|T_i(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}\right|^2\Big], \tag{8}$$

$$o_2=\sum_{i=1}^{3}CC'^{*}R_i(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}\times T_i^{*}(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}, \tag{9}$$

$$o_3=\sum_{i=1}^{3}C^{*}C'R_i^{*}(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}\times T_i(\xi,\eta)_{(\xi+x_0\cos\varphi,\eta-y_i\cos\varphi)}. \tag{10}$$

Equation (7) has 12 items, the first six items (shown as o_1) of which are auto-correlated that is useless for us and the last six items (shown as o_2+o_3, where o_2 and o_3 are conjugated) of which are cross-correlated. The joint fractional power spectra are Fourier-transformed by a lens to obtain the distribution at the output plane, which can be expressed as

$$F\left\{\left|F^p\{f(x,y)\}\right|^2\right\}=F\{o_1+o_2+o_3\}, \tag{11}$$

$$F\{o_1\}=\sum_{i=1}^{3}\left(R_i\otimes R_i+T_i\otimes T_i\right)*\delta\left(x',y'\right), \tag{12}$$

$$F\{o_2\}\propto\sum_{i=1}^{3}T_i\otimes R_i*\delta\left(x'+\frac{2x_0\left(1+\cos^2\varphi\right)}{\sin\varphi},y'\right), \tag{13}$$

$$F\{o_3\}\propto\sum_{i=1}^{3}R_i\otimes T_i*\delta\left(x'-\frac{2x_0\left(1+\cos^2\varphi\right)}{\sin\varphi},y'\right), \tag{14}$$

where ⊗ denotes correlation and ∗ denotes convolution. We use the shift-variant and phase-shifting properties of FRT in the calculation process. It is worth noticing that the joint fractional power spectra should be performed for FT, because the correlation peaks of red, green, and blue channels can be overlapped in the space after FT due to the shift-invariant property of FT. And it is also the important condition in color pattern recognition.

It has been theoretically approved that 15 correlation peaks can be obtained at the output plane in the JTC system[17], only a pair of which is useful and the others are noise that is harmful to correlation recognition. Using the new system of JFRTC, we can obtain only three correlation peaks at the output plane, one of which is a zero-order item and the other two are a pair of cross-correlation peaks that are desired in pattern recognition. The frequency spectra of red, green, and blue channels overlap at the frequency plane and then produces many correlation peaks, only three correlation peaks (red-red, green-green, blue-blue) between the target image and the reference image are desired. The correlation peaks between the target image and the reference image for red-green, red-blue, and green-blue, the correlation peaks of the target image for red-green, red-blue, and green-blue and the correlation peaks of the reference image for red-green, red-blue, and green-blue are useless. As shown in Fig. 2, there are 36 items at the output plane which form 15 locations of correlation peaks. In contrast, in the new proposed system, we can obtain the overlapped power spectra between the target image and the reference image for three color channels (red-red, green-green, blue-blue) and the fractional spectra of red-green, red-blue, and green-blue are not overlapped thanks to the shift-variant property of FRT. So the joint power spectra can yield 12 items which form only three locations of correlation peaks at the output plane (see Fig. 3).

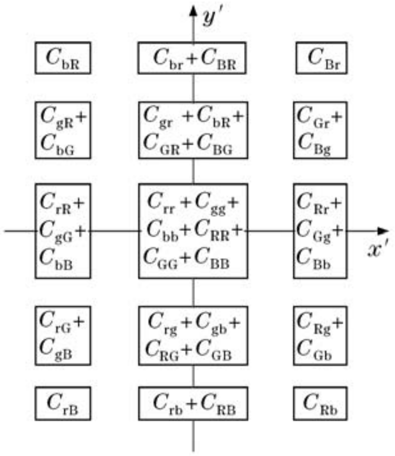

Fig. 2. Locations of the correlation peaks at the output plane in a multi-channel single-output JTC for color pattern recognition.

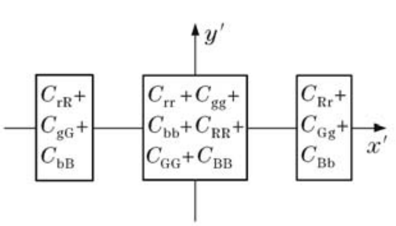

Fig. 3. Locations of the correlation peaks at the output plane in a multi-channel single-output JFRTC for color pattern recognition.

The images used for experiments are shown in Fig. 4. Figures 4(a) and (b) give the original color pictures, Fig. 4(c) is the reference image, Fig. 4(d) is the input scene target A that is the same as the reference image, and Fig. 4(e) is the input scene target B that is different from the reference image, the up-and-down interval

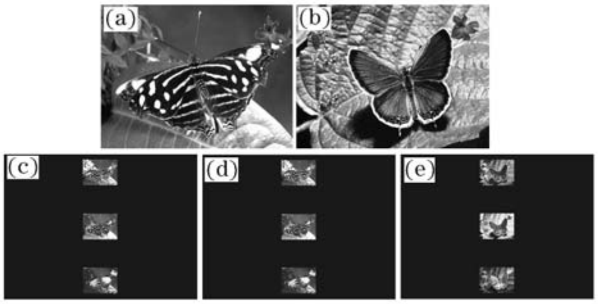

Fig. 4. Images used for experiments. (a), (b) Original color pictures; (c) input image with butterfly as the reference image; (d) input image with butterfly as the target image A; (e) input image with butterfly as the target image B.

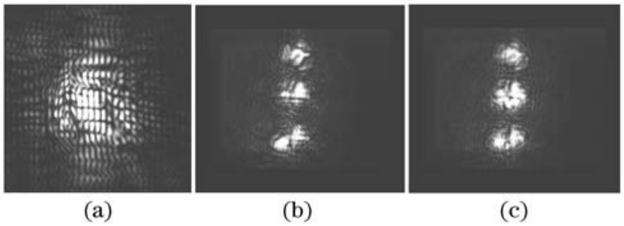

Fig. 5. (a) JTC and (b) JFRTC power spectra for the input image same to the reference image; (c) JFRTC power spectra for the input images different from the reference image.

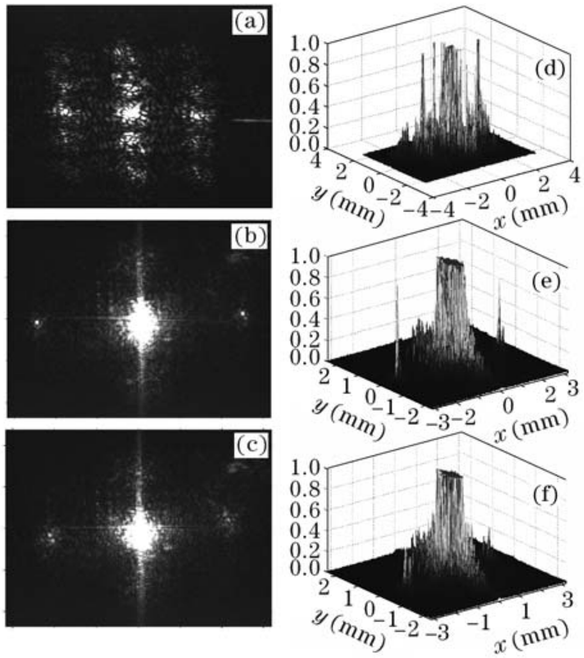

Fig. 6. (a)—(c) Experimentally obtained gray photographs of intensity distribution at the correlation plane for the power spectra in Figs. 5(a), (b), (c), respectively and (d)—(f) the corresponding 3D correlation intensity profiles.

between each two pictures in Figs. 4(c)—(e) is 150 pixels. The overall size of the input images is 1024 × 768 pixels which is equal to the size of the spatial light modulator (SLM). We investigate the performance of both the conventional multi-channel single-output JTC and the new multi-channel single-output TFRTC. The joint power spectra are shown in Fig. 5. Figure 6 shows the experimentally obtained gray photographs of intensity distribution at the correlation plane and the corresponding three-dimensional (3D) correlation intensity profiles for the joint power spectra in Fig. 5. From the 3D correlation intensity profiles we can see that when the reference image is the same as the target image, the pair of correlation peaks is sharper and has stronger intensity and less sidelobes. When an input scene object is different from the reference image, not only unconspicuous correlation peaks but also large sidelobes are produced. By calculation, we find that the discriminability ratio comes up to 0.54945, which denotes that the system has a good ability of discriminability.

In conclusion, we proposed a new system of multi-channel single-output JFRTC for color pattern recognition instead of the conventional system of multi-channel single-output JTC. With this method, we obtain three correlation peaks at the output plane which show one auto-correlation peak (it is of no use for us, and we can eliminate it by some means[18,19]) and a pair of cross-correlation peaks that is desired. Using the conventional system of multichannel single-output JTC, we obtain 15 correlation peaks at the output plane, only three of which are desired for color pattern recognition. The undesired correlation peaks play a noise role in color pattern recognition especially when relating to multi-target recognition. The proposed color pattern recognition system will positively promote the development of the pattern recognition system.

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