Rotation invariant pattern recognition with a volume holographic wavelet correlation processor

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A volume holographic wavelet correlation processor for performing rotation invariant pattern recognition is suggested. It uses wavelet transform to get the digital edge extraction of the original object and a single circular harmonic component is used as the matched filter to get good rotation invariance. The new filter used in this method is called wavelet circular harmonic component filter (WCHCF). Simulation results validate the theory and the experiment to recognize human faces with any rotation angle shows the utility of the newly proposed method.

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The associative memory characteristic of volume holographic storage in photorefractive material has been successfully used to construct optical correlators[1,2]. Once all the patterns are stored in a photorefractive material, it can be employed as a database for pattern recognition. For volume holographic correlation processor, distortion-invariant is a key problem. A limited technique for obtaining distortion-invariant pattern recognition is the use of harmonic expansion[3,4]: circular harmonic (CH) for obtaining rotation invariance[5], Mellin radial harmonic for obtaining scale invariance[6], and logarithmic harmonic for obtaining projection invariance[7].

In this paper, we propose a method which uses both wavelet transform and circular harmonic expansions, based on volume holographic correlation processor. The proposed system performs well when it is used for the recognition of human faces with any rotation angle.

The fundamentals of wavelet transform and correlation are briefly described below.

If two images are $f(x,y)$ and $s(x,y)$, respectively, their wavelet correlation is defined as[8]

$$\begin{aligned}&[f(x,y)\otimes h_a(x,y)]\otimes[s(x,y)\otimes h_a(x,y)]\\&=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}F(u,v)H^*(a_xu,a_yv)S^*(u,v)\\&\quad\times H(a_xu,a_yv)\exp[i2\pi(xu+yv)]\mathrm{d}u\mathrm{d}v,\end{aligned}\tag{1}$$

where $\otimes$ is the correlation operator, $h_a(x,y) = (\sqrt{a_xa_y})^{-1}h(x/a_x,x/a_y)$ is the wavelet filter, $a=(a_x,a_y)$ is the dilation factor of the wavelet function, and $F(u,v)$, $S(u,v)$, and $H(a_xu,a_yv)$ are the Fourier transforms of $f(x,y)$, $s(x,y)$ and $h_a(x,y)$, respectively. Mexican-hat wavelet function is used as the filter in our system, in the frequency domain it can be expressed as[9]

$$H(u,v)=4\pi^2(u^2+v^2)\exp[-2\pi(u^2+v^2)].\tag{2}$$

Circular harmonic component can be used to achieve rotation invariance. For an input object function $f(r,\theta)$ in a polar coordinate, it may be decomposed into circular harmonic components as[10]

$$f(r,\theta)=\sum_{m=-\infty}^{\infty}f_m(r)\exp(im\theta),\tag{3}$$

where

$$f_m(r)=\frac{1}{2\pi}\int_0^{2\pi}f(r,\theta)\exp(-im\theta)\mathrm{d}\theta.\tag{4}$$

Items in expression (3) are circular harmonic components (CHC) with different orders that are orthogonal with each other. If the same target was rotated by an angle α, the rotated target could be expressed as

$$f(r,\theta+\alpha)=\sum_{m=-\infty}^{\infty}f_m(r)\exp(im\alpha)\exp(im\theta).\tag{5}$$

In polar coordinate the optical correlation result can be expressed as

$$\begin{aligned}&c(r,\theta)=\\&\int_0^{2\pi}\int_{-\infty}^{+\infty}f(r',\theta')h^*(r'+r,\theta'+\theta)r'\mathrm{d}r'\mathrm{d}\theta',\end{aligned}\tag{6}$$

where $f(r,\theta)$ represents the input image and $h(r,\theta)$ is the impulse response of the optical filter. With any single harmonic component, a m-order circular harmonic filter function can be defined as

$$h(r,\theta)=f_r(r,\theta)=f_m(r)\exp(im\theta).\tag{7}$$

Figure 1(b) is the amplitude image of second order CHC of the reference face.

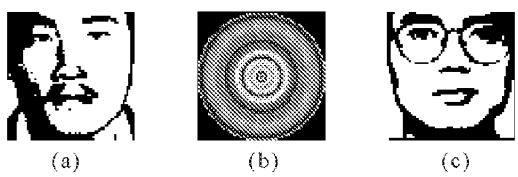

Fig. 1. A reference face image (a), its second order CHC (b), and an another image (c).

Suppose the input image was rotated by an angle α relative to the original one, then the correlation peak value would be

$$c_\alpha(0,0) = \exp(im\alpha)\int_{-\infty}^{+\infty} |f_m(r)|^2 r\mathrm{d}r. \quad (8)$$

For rotated image, the amplitude of correlation peak is independent to the rotation angle α. Thus full rotation invariance can be obtained in theory, but the discrimination capability which is very important to correlation identification system is not good enough.

Figure 2(a) is the correlation between the reference face image and its second order CHC and itself, Fig. 2(b) is the correlation between the second order CHC of the reference face image and another face image (shown in Fig. 1 (c)) which differs from the reference image. Ideally, the value of central peak in Fig. 2 (a) should be greatly bigger than the one in Fig. 2 (b), but unfortunately the central peak value of them are almost the same. At the same time the sideslobe is big and the discrimination ability is decreased too. So, the conventional CHC filter cannot be directly used to perform human face rotation-invariant pattern recognition.

To improve the discrimination capability, we introduce the wavelet circular harmonic component filter (WCHCF). First perform wavelet transform on the reference image to get the main feature image, then calculate the circular harmonic component of the new main feature image and uses it as the new filter.

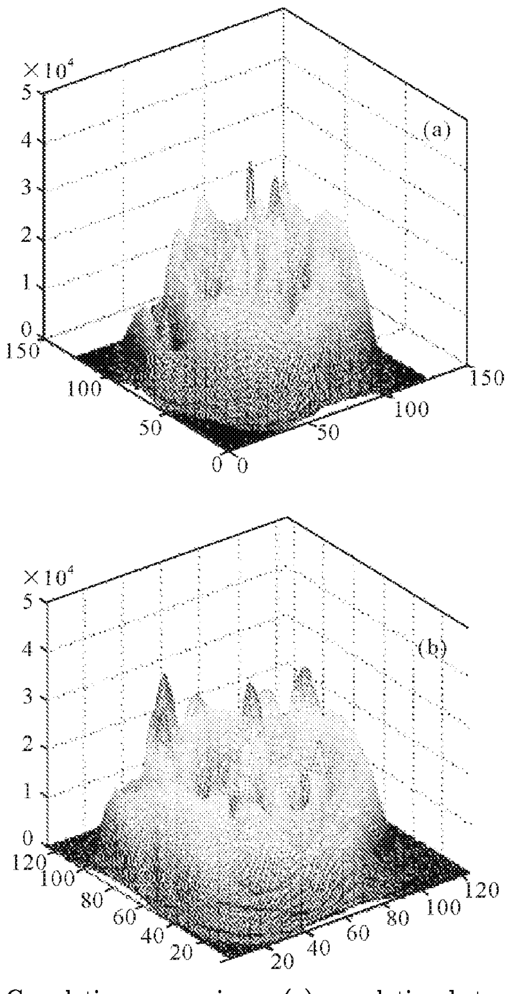

Fig. 2. Correlation comparison. (a) correlation between the reference face image and its second order CHC; (b) correlation between the same CHC and another face image.

We can use the formula below to get the wavelet transform result $W_f(x,y)$ for the reference image function $f(x,y)$,

$$W_f(x,y) = f(x,y) \otimes h_a(x,y), \quad (9)$$

Then change $W_f(x,y)$ to $W_f(r,\theta)$ in polar coordinate. The m-order CHC of $W_f(r,\theta)$ is

$$f_{wm}(r) = \frac{1}{2\pi}\int_0^{2\pi} W_f(r,\theta)\exp(-im\theta)\mathrm{d}\theta. \quad (10)$$

Defines the m-order wavelet circular harmonic filter function as

$$f_{wr}(x,y) = f_{wm}(r)\exp(im\theta). \quad (11)$$

Wavelet circular harmonic correlation is the correlation between the image's wavelet transform result and WCHCF, and can be expressed as

$$\begin{aligned} & W_f(a_x,a_y,x,y) \otimes f_{wr}(x,y) \\ & = [f(x,y)\otimes h_a(x,y)] \otimes f_{wr}(x,y) \\ & = FT^{-1}\{FT\{f(x,y)\otimes h_a(x,y)\}\cdot FT\{f_{wr}(x,y)\}^*\} \\ & = FT^{-1}\{F(u,v)H^*(a_x,a_y,u,v)F^*_{wr}(u,v)\} \\ & = FT^{-1}\{F(u,v)[H(a_x,a_y,u,v)F_{wr}(u,v)]^*\} \\ & = f(x,y)\otimes FT^{-1}\{H(a_x,a_y,u,v)F_{wr}(u,v)\}, \end{aligned} \quad (12)$$

where $F_{wr}(u,v) = FT\{f_{wm}(x,y)\}$, $FT\{\cdots\}$ represents for Fourier transform. The result means that wavelet circular harmonic correlation can be realized by using the conventional $4f$ system. The filter needed in frequency domain is $H^*(a_x,a_y,u,v)F^*_{wr}(u,v)$.

The WCHCF has rotation invariance ability and the ability to discard non-target image. Comparing with the conventional CHC filter, its discrimination capability is enhanced greatly as shown by the following results.

We perform wavelet transform on the reference image to get the main feature image by edge extraction, called wavelet reference image. Figure 3(a) is the wavelet transform result of the face image shown in Fig. 1(a). Then calculate the WCHCF that in fact is the 2-order circular harmonic component of the wavelet reference image (shown in Fig. 3(b)). Figure 3(c) is another different

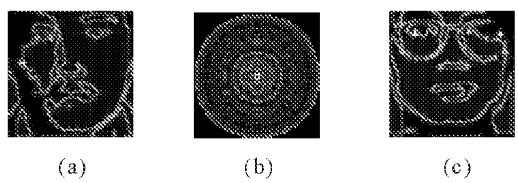

Fig. 3. (a) A reference face image's wavelet transform result, (b) its second order CHC, and (c) another different face image's wavelet transformation result.

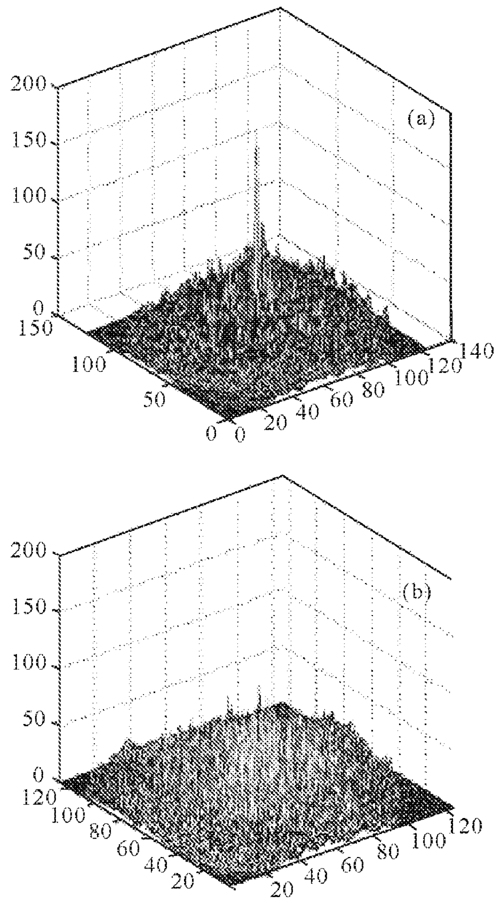

Fig. 4. Correlation comparison. (a) correlation of reference face image's wavelet transform result with its WCHCF; (b) correlation between the same WCHCF and another face image's wavelet transform result.

face image's wavelet transformation result with the same parameters.

In recognition, the wavelet transform result of the image for identification is correlated with the WCHCF made from the target image. From the correlation peak value, we can judge if it is the target image. Figure 4(a) is the correlation between Fig. 3(a) and its WCHCF (Fig. 3 (b)), Fig. 4(b) is the correlation between Fig. 3(c) and the WCHCF.

The correlation peak in Fig. 4 (a) is obviously higher than that in Fig. 4 (b), so we can judge easily that the first human face is the same as the target face, and the second image is not.

Simulated results above show the discrimination capability of the WCHCF, and rotation invariance is another important feature of the WCHCF. There are three rotated versions of Fig. 1 (a), whose rotation angles are 10, 20 and 90 degrees, respectively, as shown in Fig. 5. Their wavelet transform results are shown in Fig. 6.

Figure 7 shows the correlation between images in Fig. 6 with the WCHCF shown in Fig. 3 (b). The correlation peak values of three different rotated versions are almost same, so we can judge that they are the same as the target image (Fig. 3 (a)). This proves the rotation invariance feature of the WCHCF.

Finally, experimental result validates the utility of the newly proposed method. Figure 8 shows the volume holographic wavelet correlation processor used in the experiment[11].

The image to be recognized is displayed on the SLM, then it is Fourier transformed by a lens FL, filtered by a wavelet filter WF, and imaged onto the PR crystal by the lens IL. Rotating half wave plate HP_2 can adjust polarization direction of the object beam as that of the reference beam. The two beams interfere to form a volume hologram in the PR crystal. By moving the lens L_1 and replacing the input pattern, angle-multiplexing holograms

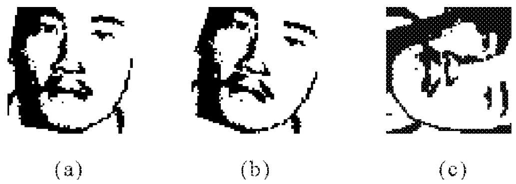

Fig. 5. Rotation versions of the reference face image (a) rotation angle 10 degree, (b) rotation angle 20 degree, and (c) rotation angle 90 degree.

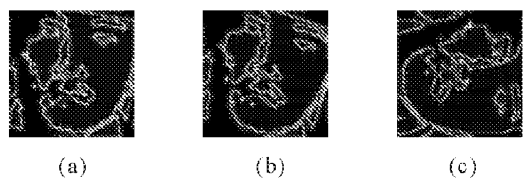

Fig. 6. Rotation image's wavelet transform result (a) rotation angle 10 degree, (b) rotation angle 20 degree, and (c) rotation angle 90 degree.

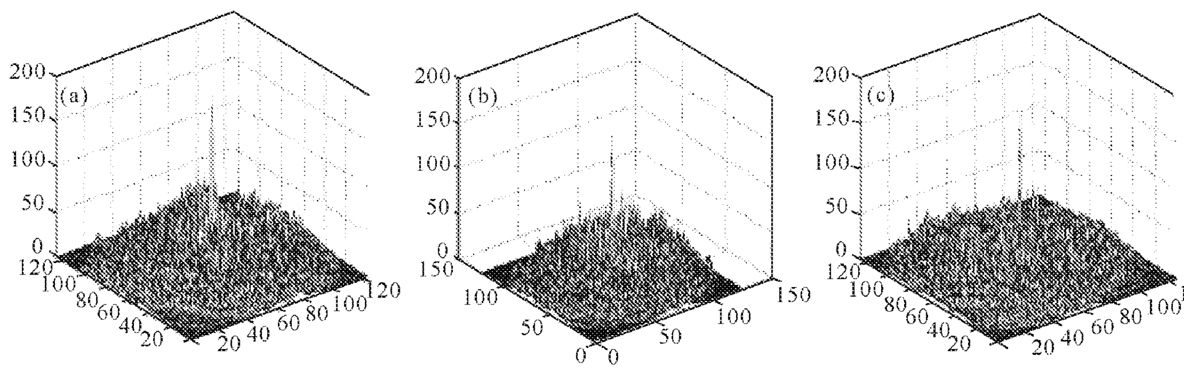

Fig. 7. Correlation comparison. (a) correlation of 10 degree rotated version with the WCHCF; (b) correlation of 20 degree rotated version with the WCHCF; (c) correlation of 90 degree rotated version with the WCHCF.

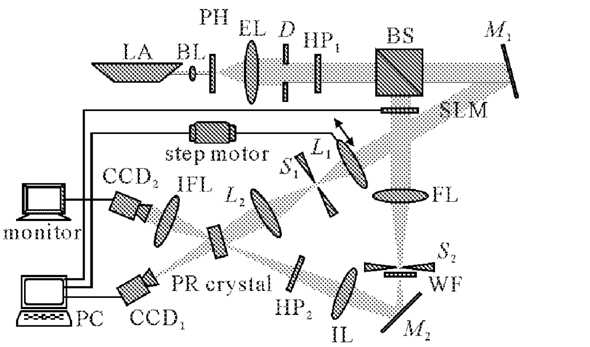

Fig. 8. A volume holographic wavelet correlation processor.

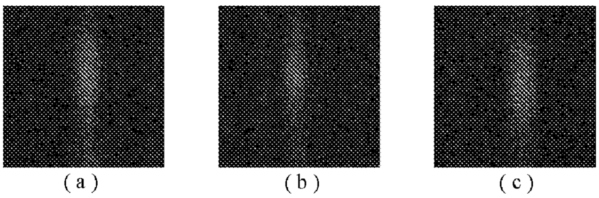

Fig. 9. Experiment correlation result. (a) correlation of 10 degree rotated version with the WCHCF; (b) correlation of 20 degree rotated version with the WCHCF; (c) correlation of 90 degree rotated version with the WCHCF.

will be recorded in the PR crystal. After the process of storing reference images, the system is ready for recognition. In recognition, the reference beam is not needed. The image to be recognized is displayed on the SLM too, then its spectrum is filtered by the wavelet filter and imaged onto the PR crystal to read out the holograms. Multichannel wavelet correlation outputs are captured by a CCD camera and transferred to a computer for processing. Hence, an input image corresponds to a correlation intensity vector. By finding the minimum distance between the vector of the input image and that of previously patterns, the input image can be recognized correctly.

The WCHCF can be applied in a processor. In the recording process the wavelet filter WF in Fig. 8 should be removed, then calculate the WCHCFs of the target images using the computer and display them sequentially on the SLM, thus the WCHCFs' frequency charts are recorded in the PR. In the recognition process, the WF should be placed back, just display the image for recognition on the SLM and the correlation output will be captured by the CCD1.

The practical human face recognition system with the WCHCF obtains rotation invariance and works better than the old one. Figure 9 is the experimental result corresponding to the simulation result shown in Fig. 7.

We have proposed a new WCHCF and applied it in the volume holographic wavelet correlation processor. Good discrimination capability and rotation invariance are obtained in the new system. The maximum rotation angle with rotation invariant is about 6 degree for the old system, and now the new system with the WCHCF can recognize the images with any rotation angles. Theory analysis about WCHCF is given. Simulation results using the human faces validate the theory. Researches on the distortion invariance are currently being investigated for a practical processor.

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