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A hetero-associative memory using phase-multiplexing references

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Abstract

We present a hetero-associative memory for multiple-associative pairs by using the phase-multiplexing technique. Two methods for reducing the cross-talk between different association pairs are proposed. An optical experiment for the edge-enhancement associative memory is also demonstrated. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Associative memory; Phase-only filter; Edge-enhancement

1. Introduction

The most interesting characteristics of an associative memory are its capability of fault tolerance and associated retrieval. In a hetero-associative memory, by presenting a partial pattern of one category, an associated pattern of another category can be obtained. Several optical holographic associative memories have been demonstrated in which the associated patterns are interconnected at the Fourier plane [1–3]. In fact, an associative memory can be regarded as a storage device that produces a closely associated output by the reading beam. However, there is a fundamental difference between the holographic storage device and the hetero-associative memory. In a phase-multiplexing holographic storage system, the encoded phase patterns are introduced into the reference beam. When the input image is an addressing phase pattern which was used during recording, then the addressed amplitude image is read out. In order to reduce the cross-talk between different phase-addressed patterns, some encoded techniques such as the orthogonal phase-coding method is used [4–6]. Thus, the input image is one of the encoding reference patterns. On the other hand, in the hetero-associative memory, the input image is not a specified pattern. Usually it is an unknown image. Therefore, the orthogonal phase-encoding technique is not applicable to the hetero-associative memory. It is interesting to see how these non-orthogonal phase patterns affect the cross-talk of the retrieved images in a hetero-associative memory, and to see how does the cross-talk limits the number of associated pairs.

In this paper, we present a hetero-associative memory by using the phase-multiplexing technique to achieve multiple associative pairs. We propose two different methods to reduce the cross-talk between different pairs. Finally, an optical system is set up to demonstrate the edge-enhancement associative

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memory. The experimental result shows that the cross-talk of the retrieved images is the limiting factor for the storage capacity of the associative memory.

2. Hetero-associative memory by using phase-multiplexing technique

Fig. 1 illustrates the schematic diagram of the optical setup for the phase-multiplexing associative memory. LCTV1, which is phase modulated and is located at the image plane of the recording material, provides the addressing beam. LCTV2, which is amplitude modulated and is located at the front focal plane of the holographic memory, is used to display the object images. After recording the holographic memory, when a phase image, $e^{-i\phi_g}$, is presented, an object image will be retrieved. Mathematically, the retrieved image on the CCD can be given by

$$I_{\text{output}} = \left| F.T.\left\{ \left[\exp(-j\phi_g)\right] \left[\sum_m \exp(j\phi_{fm}) H_m \right] \right\} \right|^2$$
$$= \left| \sum_m F.T.\left\{ \exp\left[j(\phi_{fm} - \phi_g) \right] \right\} \otimes h_m \right|^2 \quad (1)$$

where $F.T.$ means Fourier transform, ϕ_g is the phase pattern of the input image, ϕ_{fm} is the binary phase pattern of the mth reference image f_m, which was shown on LCTV1 during recording, h_m is the associated object image, which was shown on LCTV2 during recording, and H_m is the Fourier transform of h_m. From Eq. (1), it can be seen that if the input pattern matches exactly with one of the stored images, then there is a perfect phase match, i.e., $\phi_g = \phi_{fm}$. The output image will be the exact retrieval of the image h_m plus the noise comes from the cross-talk between ϕ_g and ϕ_{fm}, where $\phi_g \neq \phi_{fm}$. Thus, when only one pair is stored in the memory, a perfect phase will match the result in a reconstructed image which is exactly the associated image. For multiple pairs, the reconstructed image is a superposition of the associated image plus the cross-talk noise from other pairs.

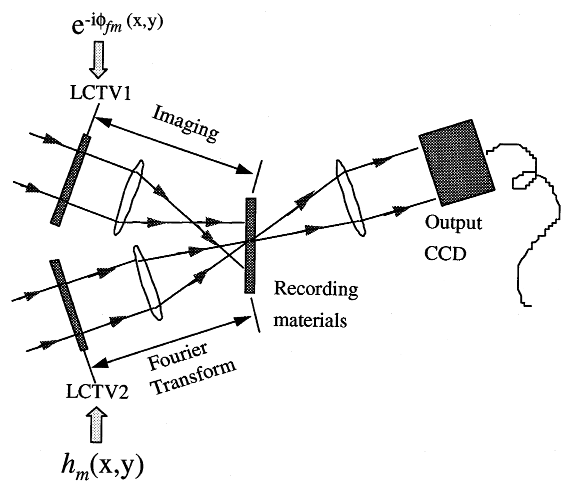


Fig. 1. The schematic diagram of the optical setup for the associative memory by using phase multiplexing technique.

Table 1
Four pairs of associative memory

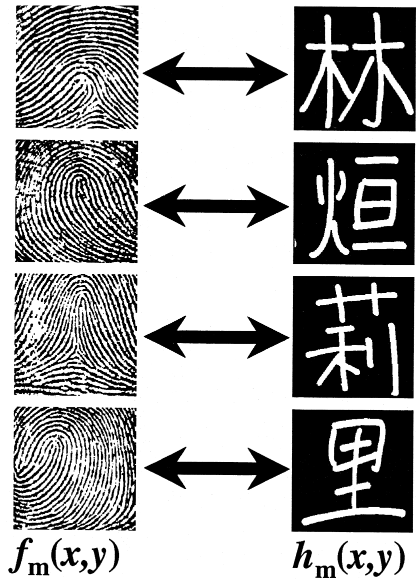
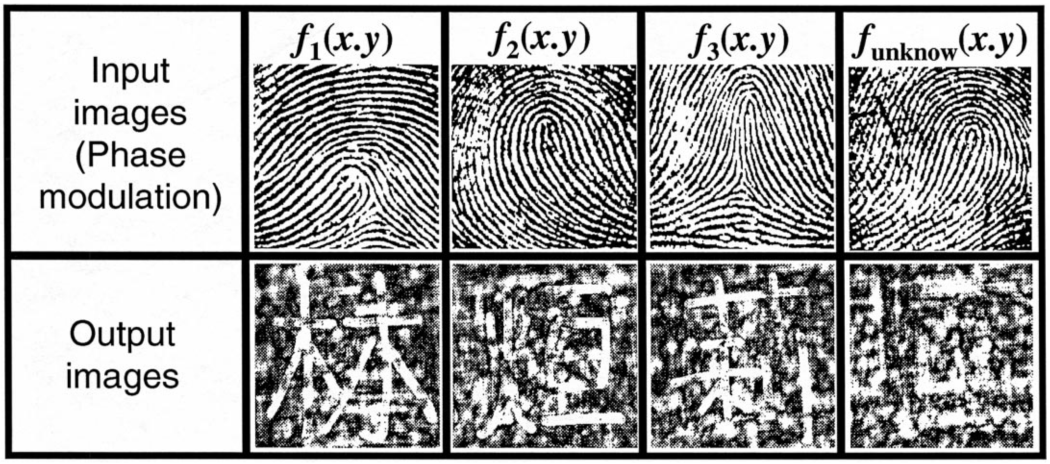


Table 1 shows four pairs of associative memory. The pixel number of each image is 256 × 256 pixels. The four fingerprints are the reference images and they are displayed on LCTV1 with binary phase modulation. The black fringes of the fingerprints were encoded into zero-phase and the bright regions were with π-phase. The four signatures of the right column are the associated images and they are dis-

Table 2
Computer simulation results of associative memory



played on LCTV2 with binary amplitude modulation. The black parts were displayed with dark pixels, which means no light passes through, and the bright regions correspond to bright pixels.

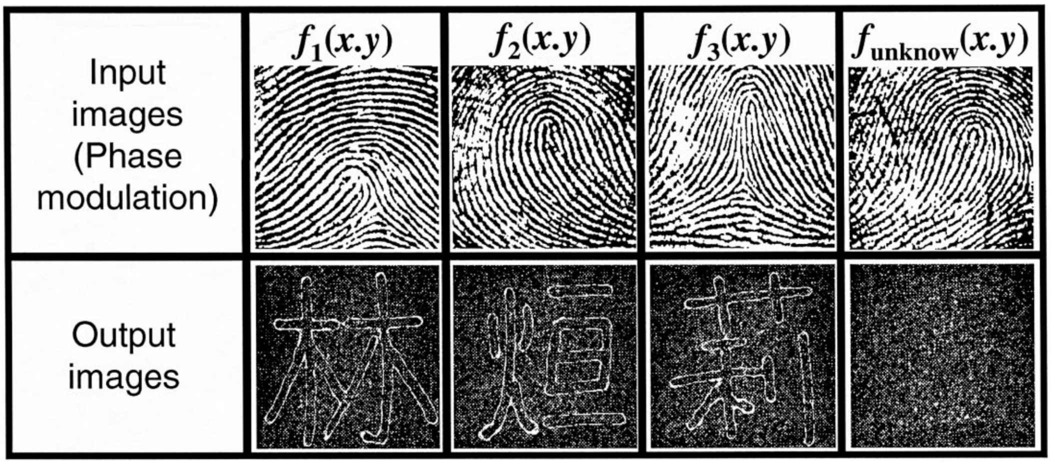
We perform a computer simulation on the associative memory. The results are shown in Table 2. The input images are shown in the upper row and the retrieved images are shown in the lower row. It is seen that when the input image is one of the reference images, the associated image can be retrieved together but with a lot of noise. As described in the previous paragraph, the noise comes from the cross-talk between different pairs. These results indicate the feasibility of the hetero-associative memory by using the phase modulated reference images. The problem is how to reduce the cross-talk noise caused by these non-orthogonal reference images.

3. Phase-only filter

Oppenheim and Lim [7] have performed an interesting study, which shows the superior significance of a Fourier phase over the Fourier amplitude. In their examples, the phase term of the Fourier transform of image A was multiplied with the amplitude term of the Fourier transform of image B, then inverse Fourier transformation of the multiplication was used to give an image that was similar to image A. On the other hand, the phase term of the Fourier transform of image B was multiplied with the amplitude term of the Fourier transform of image A, then inverse Fourier transformation of the multiplication produced an output image that resembled image B. The result showed that the phase term of the Fourier transform of an image is more significant than the amplitude term for reconstructing the stored image. This characteristic has been widely used to improve the performance of the filter [8–10]. Thus, instead of using the Fourier transform H_m, we used the phase term of H_m to form the associative memory in the filter plane. Since both the reference and the associated images are phase modulated, the filter is therefore named the phase-only filter. Then, the reconstructed image on the CCD can be written

$$I_{\text{output}} = \left| F.T.\left\{ \exp\left[-\mathrm{j}\phi_g\right] \sum_m \exp\left[\mathrm{j}\phi_{fm}\right] \frac{H_m}{|H_m|} \right\} \right|^2 = \left| \sum_m F.T.\left\{ \exp\left[\mathrm{j}\left(\phi_{fm} - \phi_g\right)\right] \right\} \otimes F.T.\left\{ \frac{H_m}{|H_m|} \right\} \right|^2 \quad (2)$$

Table 3
Computer simulation results of associative memory with phase-only filter



where $H_m/|H_m|$ represents the Fourier phase of the image h_m. Computer simulations are performed and the results are shown in Table 3. Again, the first row in Table 3 shows the input images and the second row shows the corresponding output images, respectively. It is seen that the cross-talk noise is reduced and the quality of the retrieved images is improved.

Under special conditions, the phase-only filter can be realized by the optical technique. It can be proved that when the original image, h_m, is a real function then the inverse Fourier transform of $H_m/|H_m|$ is also real. In our case, the associated image h_m is amplitude modulated, hence it is a real function and thus the inverse Fourier transform of $H_m/|H_m|$ is real. This means that the inverse Fourier transform $H_m/|H_m|$ can be displayed on a amplitude modulated spatial light modulator (SLM). Then, the Fourier transform of the display gives $H_m/|H_m|$, which is the phase information of H_m. For optical implementation, the inverse Fourier transform of $H_m/|H_m|$ should first be calculated by computer. The result is displayed on the amplitude-modulated SLM. The Fourier transform of this function interferes with the corresponding phase reference image at the filter plane and a phase-only filter can be obtained.

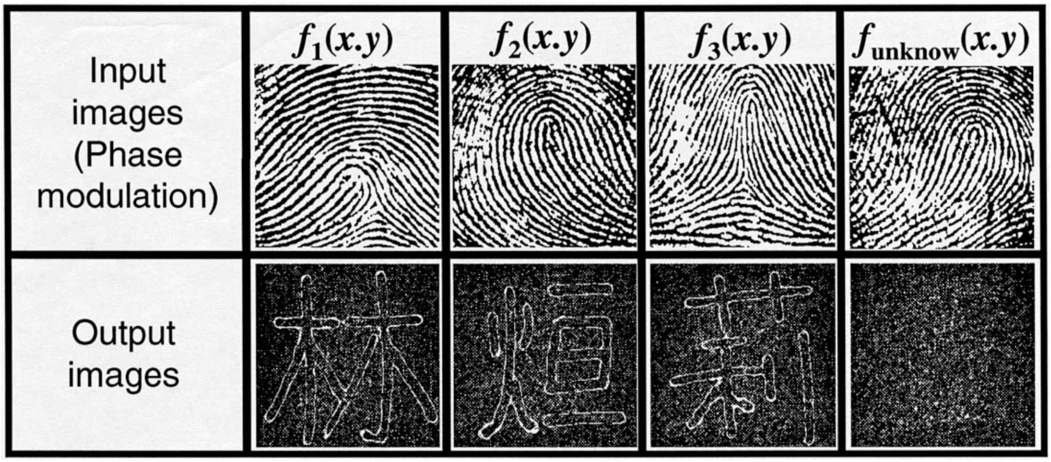
4. Edge-enhancement associative memory

In Table 3, it can be seen that the output images of the phase-only filter posses the edge-enhancement characteristic. In physical situation, the Fourier phase represents the high frequency part of the image h_m. Since the phase-only filter takes only the phase term of the Fourier transform H_m, then image retrieval from the phase-only filter gives the high frequency part of the image h_m. Therefore, it can be seen that the retrieved images present an edge-enhancement effect. This edge-enhancement characteristic can be ultilized to construct an optical associative memory. During the recording stage, instead of the using the phase term of the Fourier transform of h_m on the filter plane, the high frequency part of H_m is used. The retrieved image on the CCD can be expressed by

$$I_{\text{output}} = \left| F.T.\left\{ \left[\exp(-\mathrm{j}\phi_g)\right] \sum_m \exp(\mathrm{j}\phi_{fm})\, Highpass(H_m) \right\} \right|^2$$

$$I_{\text{output}} = \left| \sum_m F.T.\{\exp[\mathrm{j}(\phi_{fm} - \phi_g)]\} \otimes F.T.\{Highpass(H_m)\} \right|^2 \qquad (3)$$

Table 4
Computer simulation results of edge-enhancement associative memory



where

$$Highpass(H_m) = \begin{cases} 0, & \text{if} \quad u \le u_0 \\ H_m, & \text{if} \quad u > u_0 \end{cases},$$

where u is the spatial frequency, u_0 is a specified thresholding value, and $Highpass(H_m)$ represents a high-pass filter. Table 4 shows the results of computer simulation for the edge-enhancement associative memory. The first row shows the input fingerprint images, which are phase modulation images. The second row shows the corresponding retrieved images. When the input image is one of the reference

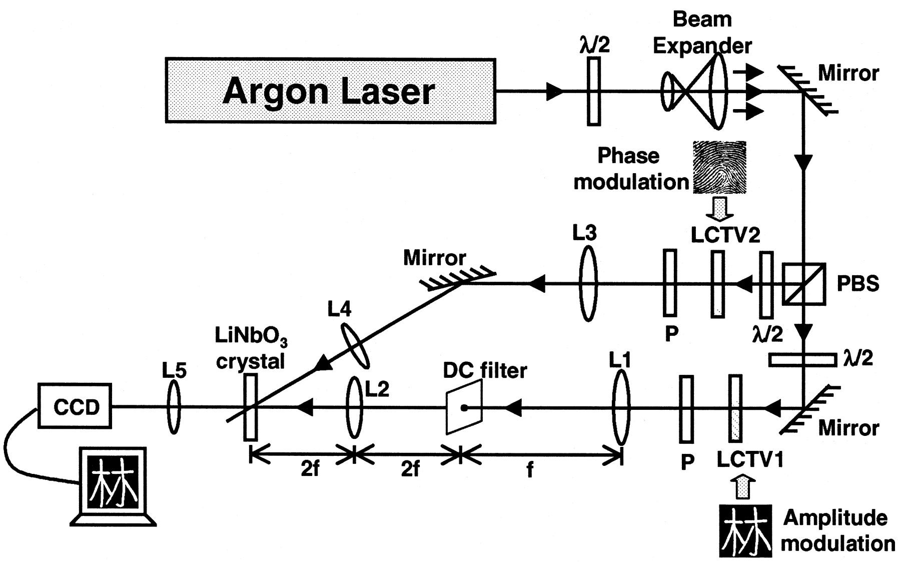
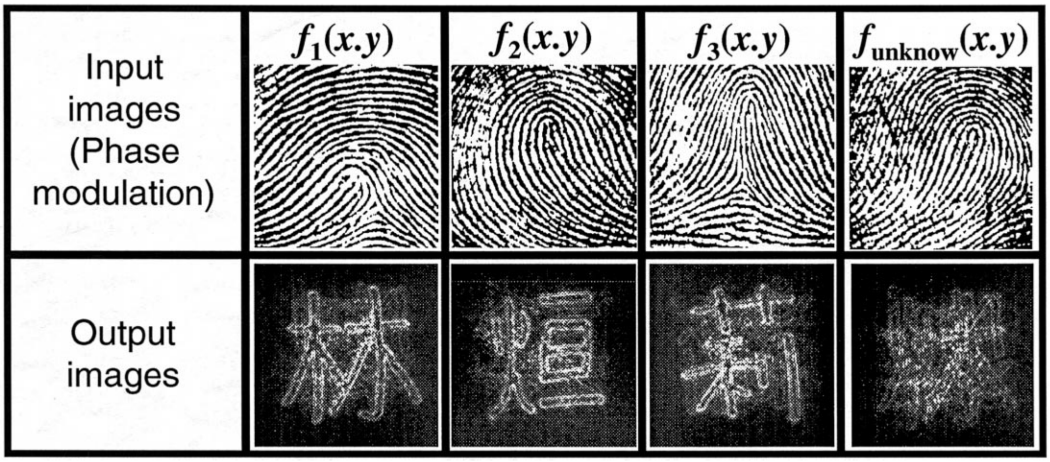


Fig. 2. Optical experimental setup for edge-enhancement associative memory.

Table 5
Experimental results of edge-enhancement associative memory



phase images, the output image is retrieved correctly. The results show that the edge-enhancement technique provides the associative memory with a quality almost equal to that of the phase-only filter technique.

The setup for the edge-enhancement type of the associative memory is shown in Fig. 2. An argon laser beam is expanded, collimated, and split into two plane waves. One beam passes through the LCTV1, which operates in amplitude modulation mode to show the associative images. The second beam passes through LCTV2, which operates in binary phase modulation mode to show the reference fingerprints. The associated image is Fourier transformed by L1, and the reference image is imaged by L3 and L4 on the holographic recording medium. The DC filter is a transparent glass plate with a black spot at the center. It acts as a high-pass filter for the associated image. The interference fringes produced by the associated pairs are recorded at one spot on the $LiNbO_3$ crystal by using multiple exposure technique. After the multiple pairs have been recorded, the object beam is blocked and the input image is presented on LCTV2. Then, the associated image will appear at the CCD plane.

Experimental results of the edge-enhancement associative memory are shown in Table 5. It can be seen that when the input image is one of the reference images, the corresponding associated image is retrieved. When the input image is not one of them, then the output image is not recognizable. The system shows the capability of discrimination between different memory pairs.

5. Discussion

In the above description, the associative memory has recorded only four pairs of images. In the following, we discuss the storage capacity of this system.

We have performed a computer simulation on the effect of increasing the number of storage pairs in the associative memory. Each time after all the image pairs of the associative memory are recorded, the input images are presented to test the performance of the system. Then, we recorded a new memory, of which the number of storage pairs is increased by one and the system performance is tested again. Both the phase-only filter and edge-enhancement techniques are used for this study. The two methods show similar results. When there are less than six storage pairs, all the stored pairs can be retrieved correctly. When the number of storage pairs is increased to more than six, the output images come with too much cross-talk and are not recognizable. Therefore, the storage capacity of this non-orthogonal phase reference associative memory is apparently limited to about six.

6. Conclusion

We have used a phase-modulated SLM as the reference pattern to construct a hetero-associative memory. Two different techniques, the phase-only filter and edge-enhancement, are proposed. Computer simulation shows that the two techniques are suitable for associative memory. We have presented an optical implementation for the edge enhancement type associative memory. Experimental results show a good discrimination between the associated pairs. A computer simulation was performed to study the storage capacity of the associative memory. The results show that for this non-orthogonal phase reference system, the storage capacity is limited by the cross-talk noise.

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