Conjugate Image Plane Correlator with Holographic Disk Memory

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A conjugate image plane correlator with holographic disk memory is proposed. Optical correlation between conjugate images reconstructed from a holographic disk and an input image on liquid-crystal television is executed with the rotation of the disk. Regardless of Fourier hologram recording with the pseudorandom diffuser, it is found possible to take out the diffuser from the original hologram recording scheme using an image reconstruction process and to get correlation signals between input and reconstructed conjugate images in the output plane of a two-lens imaging system. Generation of conjugate replicas with high contrast causes exact matching with an input image which results in high recognition performance for autocorrelation signals. The transfer function of an optical system can be controlled by adjustment of either hologram size or hologram area illuminated with a laser beam. Hence, the output intensity distribution can be adjusted by selecting a proper pupil function and the size of an output pupil defined by the input pupil size and the optical system magnification factor. The real-time character recognition by optical parallel high-speed processing for two-dimensional images with position normalization is demonstrated.

Key words: correlator, conjugate image plane correlator, Fourier hologram, pseudorandom diffuser, holographic disk memory, character recognition.

1. Introduction

As a correlation function generator an optical correlator is attractive for optical image processing and pattern recognition. It can work at the speed of light, and can employ parallel processing easily. In the conventional Vander Lught correlator, an processing operation is usually carried out in the Fourier plane with a complex spatial filter. This type of coherent optical processor can perform many complicated processing operations. However, the main disadvantage of the Vander-Lught correlator is its hard filter arrangement. Therefore, use of a number of filters on a moving carrier in this correlator is not practical. An image-to-image correlator is another type of correlator which is useful for detection of image matching. Coherent nonholographic image-to-image correlators and an incoherent image casting system using transparencies have been developed in the past. However, for conventional image-to-image correlators, the corresponding images on two transparencies are never identical, and alignment is hard. Alignment strongly influences the intensity of the correlation signals and the recognition performance of the system. In the last few years, optical-disk-based systems with high speed optical parallel processing have been investigated. In this paper, we propose a conjugate image plane correlator with a holographic disk using either coherent or partially coherent illumination which overcomes the above mentioned disadvantages and provides high speed optical parallel processing.

2. Principles

Imaging with concomitant image processing can be realized by a holographic recording and reconstruction technique. The holographic method of information registration provides a natural parallelism of recording and reading procedures for two-dimensional data. Fourier transform holograms have the advantages of shift-invariant property and high recording density with redundancy. Combination of parallel access with high data retrieval rates (200 Mbit/s) and large storage capacity (500 Mbyte on a disk 150 mm in diameter) makes holographic-disk-based architecture well suited for optical signal processing, optical computing, and efficient implementation of neural networks.

Fourier holograms recorded on the disk carrier may serve as a library of references in an image plane correlator. Therefore, in the first step, the reference images are recorded on a holographic disk in sequence by means of Fourier holograms. The liquid-crystal television (LCTV) with input information is illuminated with coherent light and a Fourier-hologram of the object image is recorded using a collimated reference beam.

2.1 Conjugate Image Plane Correlator with Holographic Disk Memory

Let us consider imagery in the two-lens diffraction system of Fig. 1. A Fourier hologram illuminated with the conjugate $R^*$ to the original reference laser beam $R$ is a light source in the input pupil of FTI for this optical system, which reconstructs the conjugate image $o^*$ back on the object plane $P_2$. The same optical elements form a series of images of the object in plane $P_2$ and also form a series of images of the aperture stop in plane $P_3$. If LCTV is located at the back focal plane of FTI, FTI lens yields
a reconstructed image of Fourier hologram in plane \( P_2 \) without phase errors. Also, if the distance between lenses \( \text{FTL1 and FTL2} \) is \( f_1 + f_2 \), an image of the input pupil is formed in plane \( P_3 \) as the output pupil with the magnification \( f_3 / f_2 \). Thus, FTL2 lens yields an inverse Fourier transform of the complex amplitude distribution in plane \( P_2 \) again with no phase errors. Hence, the two lens system can form an image of the input pupil in output plane \( P_3 \) without phase errors. When the reconstructed conjugate wave propagates back through the optical system, all the regions of the input image on \( \text{LCTV} \), where the conjugate images are exactly matched, will allow to pass light, and an image of the input pupil is formed in output plane \( P_3 \). Therefore, if the reconstructed image \( o^*(x,y) \) is matched with the input \( i(x,y) = o(x,y) \), the full image of the input pupil appears in the output pupil plane \( P_3 \) with maximum light intensity. If the input image \( i(x,y) \) is different from \( o(x,y) \), the mismatched regions on \( \text{LCTV} \) will not pass light, so the light intensity in the output plane will decrease. Hereafter we assume that the input is a real object and its amplitude is proportional to the square root of intensity transmittance.

In the recording step of the Fourier hologram, the object wave appearing from the \( \text{LCTV} \) in plane \( P_1 \) can be written as

\[
o(x,y) = |o(x,y)| \exp[-i\phi(x,y)],
\]

(1)

where \( |o(x,y)| \) is the amplitude of the input object, and \( \phi(x,y) \) is its phase distortion due to \( \text{LCTV} \). The complex amplitude distribution \( O(u,v) \) reached in plane \( P_1 \) is proportional to the Fourier transform of \( o(x,y) \)

\[
O(u,v) = \int o(x,y) \exp[-2\pi i (ux + vy)] dx dy.
\]

(2)

If the pseudorandom diffuser (PRD) is superimposed with \( \text{LCTV} \), the complex amplitude distribution in plane \( P_1 \) is given by

\[
O_d(u,v) = O(u,v) \ast G(u,v),
\]

(3)

where \( G(u,v) \) is the Fourier transform of the amplitude transmittance of the diffuser \( g(x,y) \), and \( \ast \) denotes convolution.

The intensity distribution \( I_d(u,v) \) in plane \( P_1 \) is given by

\[
I_d = |O_d(u,v)|^2,
\]

(4)

where the asterisk denotes the complex conjugate. The optical setup for Fourier hologram recording with

PRD is shown in Fig. 2 and the hologram size, \( d_h \), is determined by the focal length \( f_3 \) of FTL1, the recording wavelength \( \lambda \), and the aperture size of the sampling element of the diffuser, \( \beta_d P_3 \). That is,

\[
d_h = \frac{2\lambda f_3}{\beta_d P_3},
\]

(5)

where \( \beta_d \) is the ratio of the aperture width to the sampling pitch. For example, if \( \lambda = 0.63 \mu m, f_3 = 60 \mu m, \beta_d = 1 \), and \( P_3 = 14 \mu m \), the hologram size \( d_h \) is equal to 4.5 mm.

In the reconstruction step, the hologram on the disk is illuminated with the conjugate \( R^* \) to the original reference beam \( R \). The hologram reconstructs the conjugate to the original object wave whose complex amplitude in the hologram plane is \( O^*_d \).

When this wave propagates back through the lens \( \text{FTL1} \), a diffraction-limited real image of the object is formed in its original position in plane \( P_3 \). Complex amplitude can be written, apart from a constant factor relating to PRD, as

\[
o^*(x,y) = |o(x,y)| \exp[i\phi(x,y)].
\]

(6)

If we input an image into \( \text{LCTV} \) (or SLM) with the amplitude transmittance \( i(x,y) \), the light field \( c_i(x,y) \) at each point immediately behind the \( \text{LCTV} \) is proportional to

\[
c_i(x,y) = o^*(x,y) i(x,y).
\]

(7)

The amplitude distribution in plane \( P_3 \) is

\[
c_i(p,q) = O^*(p,q) \ast I(p,q),
\]

(8)

where \( O^*(p,q) \) and \( I(p,q) \) are Fourier transform of \( o^*(x,y) \) and \( i(x,y) \), respectively, \( p, q \) are spatial frequency variables in plane \( P_3 \), and \( \ast \) denotes convolution.

It is desirable and more useful for practical applications to generate the correlation signal in this optical system. The optical setup for the conjugate image plane correlation system is shown in Fig. 3(a), from which PRD used in the hologram recording process has been removed. The correlation signal can be obtained easily by relative motion of the reconstructed image and the input image on \( \text{LCTV} \) by rotation of a holographic disk. In the reconstruction process, the carrier of Fourier holograms will rotate in the hologram plane according to disk rotation on angles of approximately \( a = r/2L \), where \( r \) is the radius of the
hologram recorded and \( L \) is the radius of the track recording the hologram on the disk. Consequently, the reconstructed image from a hologram will move with uniform velocity but with not equal displacement in \( x \) and \( y \) directions.

If the additional lens \( L_0 \) is used to yield Fourier transform, the light field in plane \( P_1 \) in Fig. 3(b) will be

\[
c_0(x, y) = \delta^*(x-x_0, y-y_0)h(x, y)e^{i\theta(x, y)}
\]

(9)

where \((x_0, y_0)\) represent the displacement of \( \delta^*(x, y) \) with respect to the input \( i(x, y) \) and \( \theta(x, y) \) is a phase shift between the phase conjugation and the reconstructed beam due to rotation of the holographic disk. Note that this distribution will be directly measured by a photodetector that responds only to light intensity. Since the term modifies only the phase distribution of the light, it will have no effect on the results of the intensity measurement. Thus, the total light intensity in plane \( P_1 \) or plane \( P_3 \) after additional Fourier transform by lens \( L_0 \) will be

\[
I_0(x_0, y_0) = \int_0^\infty |\delta^*(x-x_0, y-y_0)h(x, y)|^2dS
\]

(10)

where \( S \) is the area of the input image illuminated with light. \( I_0(x_0, y_0) \) represents the total intensity obtained by integration of square values of the product of the complex amplitude of the conjugate reference image and the amplitude transmittances of the input object on LCTV (or SLM). Note that, if the input is an intensity transmittance object and \( i(x, y) = \delta(x, y) \), the maximum intensity of the output signal is obtained when \( x_0 = y_0 = 0 \), which corresponds to the autocorrelation peaks between the intensity of conjugate reference image and the intensity transmittance of the input image.

Note also that it is difficult to get the correct phase conjugation under the reconstruction process for Fourier hologram recording because of the wide range of spatial frequencies. Therefore, PRD is taken out from the optical system under the reconstruction process. In this case, at first glance the optical system shown in Fig. 3 may not look suitable for correlation signal detection, since the Fourier hologram may reconstruct a phase conjugate wave which does not get full distortion compensation because of the absence of PRD in the reconstruction process. However, this is not true with careful investigation of the system. When the Fourier hologram recorded with PRD is illuminated with a laser beam of 1 mm diameter or so, the reconstructed conjugate wave will contain high frequency PRD components. Hence, it is advisable not to retain the PRD in the reconstruction process. Its role in the recording process is to give a fairly uniform intensity distribution of the character frequencies of the input object.

A phenomenon of partially coherent illumination of the optical system takes place, because of image reconstruction from the Fourier hologram recorded with PRD under disk rotation. In the optical system of Fig. 3, the output pupil in plane \( P_2 \) is the image of the input pupil, and the pupil function is equal to the coherent transfer function. The transfer function of the optical system in this figure can be controlled by adjustment of the source diameter of reconstruction beam \( R^* \). Thus, the diameter of the output pupil \( r_o \) is determined by the diameter of input pupil \( r_0 \) or that of the reconstruction beam \( R^* \) incident on the hologram and focal lengths \( f_1 \) and \( f_2 \) of FTI1 and FTI2, that is,

\[
r_o = r_0 f_1 / f_2 .
\]

(11)

For example, if \( r_0 = 2 \text{ mm}, f_1 = 50 \text{ mm} \) and \( f_2 = 58 \text{ mm} \), then \( r_o = 2.16 \text{ mm} \), and if \( r_0 = 1.5 \text{ mm} \), then \( r_o = 1.74 \text{ mm} \).

If the reconstructed image \( \delta^*(x-x_0, y-y_0) \) from the hologram on the disk is the phase conjugate image of the input image \( i(x, y) = \delta(x, y) \), and if \( x_0 = y_0 = 0 \), all image points in the reconstructed image overlap the corresponding points in the input image on LCTV. The light intensity in output plane \( P_3 \) becomes maximum and provides a sharp autocorrelation peak. This property of the correlation function is useful for pattern recognition. Note that, even for Fourier hologram recording with PRD, the amplitude of reconstructed wave \( \delta^*(x, y) \) is still proportional to that of the input object \( \delta(x, y) \). This is an important feature in image-to-image correlation signal detection.

3. Experimental Results

Normally the exposure characteristics of holographic recording materials are nearly linear only in the limited region. Light exposure intensities over a certain value will contribute to nonlinear distortions. Using PRD in front of LCTV, Fraunhofer diffraction of a regular rectangular aperture appears in the Fourier plane with fairly uniform light intensity distribution around the zero order. Therefore, the linear recording of Fourier hologram on photo-
sensitive material is easily realized. Generation of high quality holograms with a liquid-crystal SLM has been demonstrated by Kato et al. The LCTV panel suffers spatially from irregular transmittance characteristics even though it is illuminated with a collimated beam. Uniformity of the LCTV transmittance, however, is greatly improved by superposing PRD on the front surface of the LCTV panel.

To record Fourier holograms we have used a SHARP projection type LCTV with a pixel aperture of about 170×170 μm², and silver halides Agfa 10E75 photographic plates or DuPont photopolymer. The main advantage of photopolymer is that the material is self-developing and processing is completely dry. Hence, electronic control for the hologram recording process was realized. In order to reduce false alarms under the correlation procedure, Fourier holograms have been recorded with diffraction efficiency control. Deviation of the diffraction efficiencies of recorded holograms was within 5%.

For a system performance demonstration Fourier holograms of seven Chinese characters, symbolizing the names of different countries, were recorded on the holographic disk in sequence. Each pattern has dimensions of 17×17 pixels. The images reconstructed from the Fourier holograms recorded on Agfa 10E75 photographic plate with a size dₜ=2 mm are shown in Fig. 4. Figures 5(a) and (b) show experimental results of image-to-image superpositions of the reconstructed image of l and l and the input image l on LCTV, respectively. Light passes through the LCTV only in the regions where the reconstructed image of Fourier hologram and the input image are overlapped. Thus difference of the overlapped regions in Figs. 5(a) and (b) reflects that of correlation signals in output plane Pₐ of the system.

Figure 6 demonstrates the possibility of an optical system transfer function adjustment by changing the diameter of the laser beam incident to the hologram. The left and right of Fig. 6(a) show the light intensity distribution in output plane Pₐ and the corresponding reconstructed image in plane Pₐ for reconstruction of Fourier hologram with a laser beam with the diameter of rₜ=1.5 mm, respec-
Optical parallel access to information and simplicity of information retrieval from the holographic disk provide a mechanism for high data retrieval rates and concomitantly large processing speeds. Experimental results show high-speed information processing abilities in the holographic-disk-based correlation system. The major achievement of the proposed system is the high operation rate, about 2000 frame/s, hence it is quite competitive with digital signal processing by an electronic computer.

We can determine the speed of the system for information processing. One hologram with a diameter of \(d = 1\) mm may contain a data matrix with dimensions of \(400 \times 400\) bits, and the available distance between neighboring holograms is about 1mm. For disk rotation with a speed of 1122 rpm (commercially available driver for CD), the transition time from one hologram to another is 170 ms for a track radius of 50 mm. Since each hologram consists of \(16 \times 10^6\) connections, the average processing rate is about

\[
V_r = 2 \times 16 \times 10^6 / (1.7 \times 10^{-4} - 18.8 \times 10^6) \approx 18.8 \times 10^6\text{connections/s}. \quad (12)
\]

For experiments, we have used the motor of a CD player and DuPont photopolymer pasted on the surface of a CD substrate without tracks. The wobbling and disk center offset lead to nonuniformities in the reference image location with respect to the input system. Therefore, the autocorrelation signal had an intensity variation with disk rotation. These nonuniformities should be overcome by tracking control in order to generate accurate correlation signals.

4. Conclusion and Discussion

A conjugate image plane correlator with holographic disk memory is proposed. Optical correlation between the conjugate images reconstructed from a holographic disk and the input image on LCTV is executed while the disk is rotating. Generation of conjugate replicas with high contrast causes an exact matching with an input image which results in high recognition performance for autocorrelation signals. Partially coherent processing is realized when an image is reconstructed from moving Fourier holograms recorded with PRD. The transfer function of an optical system can be controlled by adjustment of the hologram area illuminated with a laser beam. It was found that regardless of Fourier hologram recording with PRD it is possible to take out the diffuser from the original hologram recording scheme and get correlation signals between the input and reconstructed conjugate images at the output plane of the two-lens imaging system under the image reconstruction process. Image reconstruction from a moving Fourier hologram recorded with PRD requires consideration of the proposed conjugate image plane correlator as a partially coherent processing system.

The conjugate image plane correlator has several key advantages:

(a) The conjugate image, reconstructed from the hologram imaged back on the input plane, causes aberration compensation and allows exact reconstructed image superposition with the input image on the LCTV plane. The
conjugation between input and reconstructed images causes the high signal to noise ratio (SNR) of correlation signals with moving holograms when the disk rotates.

(b) The same optical setup can be used both for hologram recording and correlation signal processing. The same device (LCTV) has been used as an input SLM for hologram recording and as an input image device in the correlation system. Therefore, image matching between the points composing the conjugate reconstructed image and those of the input image on LCTV is ideal for \( o(x-x_0,y-y_0)=i(x,y) \), and the correlation signal is sharply peaked in the output plane.

(c) The proposed optical correlator can be used for partially coherent processing. This processing avoids speckle noise problems.

The conjugate image plane correlator system, unlike the Vander Lugt correlator, does not provide invariance to the shift for the input image. But this disadvantage can be compensated by recording a large number of reference images in order to obtain reliable recognition. The proposed type of correlator is attractive for position and shape control of input objects and image classification with position normalization. It can find applications in automatic character recognition, target detection and robotics vision. Automatic translation of foreign language documents is one of the available applications. Also, the proposed conjugate image plane correlation system is attractive for neural network (NN) model implementations. Real time learning algorithms can be realized in this system with in situ recording materials (photopolymers or photothermoplastics), because the same optical system is used for both interconnection weight recording and image-to-image correlation.

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