Real Time Optical Correlator with a Bi$_{12}$SiO$_{20}$ Crystal

Katsuyuki OKADA, Koji ITO, Toshio HONDA and Jumpei TSUIJUCHI

Department of Image Science, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba, 263 Japan
(Received September 12, 1994)

In this paper we propose a new design of a joint transform correlator in which two transform lenses are used to minimize the influence of their aberration, and a magnification lens is used to make the optics compact. Experimental results show the correlator can be used to recognize characters and/or half tone images in real time.

Key words: correlator, photo-refractive crystal, joint transform correlator, optical computing, image recognition

1. Introduction

Searching and recognizing objects are basic operations in associative memories and computer vision. For these purposes, correlation is one of the most important procedures; however, the operation requires enormous computation. For example, taking correlation of two 1000 × 1000 pixels’ images with TV frame ratio requires at least a few giga-operations per second (10$^9$ operations/second), and this cannot really be done with a conventional digital computer. On the other hand, optical methods have inherent advantages in parallel processing capability and high speed operation.

An optical joint transform correlator is a promising new technique. We have proposed a joint transform correlator with a photo-refractive crystal, that takes correlation between the image of an unknown object and a flexible set of reference images.

The performance of the correlator, however, is restricted by the aberration of the lens and by the thickness of the crystal; these reduce the accuracy of the obtained correlation. This paper discusses the influences of these restrictions, and presents a new design for an optical system able to take correlation of high resolution images.

2. A Basic Optical Joint Transform Correlator

Figure 1 shows a basic optical joint transform correlator with a photo-refractive crystal. At the input plane of the system, two transparencies, one the image of an unknown object $O(x+h,y)$ and the other a set of reference images $R(x, y)$, are placed side by side and are illuminated by a parallel coherent light from an Ar$^+$ laser. The lens $L_1$ creates their transformed pattern on the focal plane. The intensity distribution $I_f$ on this plane is

$$I_f \propto |\mathbb{F}[O(x, y)+R(x, y)]|^2$$

$$= |\mathbb{F}[O(x, y)]|^2 + |\mathbb{F}[R(x, y)]|^2$$

$$+ 2\Re\{\mathbb{F}[O(x, y)]\mathbb{F}^*[R(x, y)]\}$$

where $\mathbb{F}[\cdot]$ denotes the Fourier transform and asterisk (*) denotes complex conjugate. This intensity distribution produces refractive index modulation in the photo-refractive crystal. We used a Bi$_{12}$SiO$_{20}$ (BSO) for the crystal because it is well balanced in response time, diffraction efficiency and stability. A light beam from a He-Ne laser illuminates the crystal through a half mirror, and the diffracted beam is transformed by another lens to create the correlation pattern between the input images.

Since BSO crystal is sensitive for the light of short wavelength but not for that of long wavelength, the processes of writing by the Ar$^+$ laser and reading by the He-Ne laser can proceed independently, and the correlation of the images can be obtained in real time.$^{1,2}$

3. Separate Transform Lens Configuration

One disadvantage of the correlator’s design in Fig. 1 is the necessity for a large Fourier transform lens, which covers two sets of input images. This causes the system to be heavy and makes it expensive, and the aberration of the large lens reduces the intensity of the correlation peak. Assuming that the spherical aberration is dominant, the wavefront aberration $W$ can be expressed by a fourth order polynomial,

$$W = ar^4 + br^2$$

where $r$ (0 ≤ $r$ ≤ 1) is the normalized radial coordinate on the pupil plane. To minimize the wavefront aberration, the coefficient of defocus $b$ is usually set opposite the coefficient of the fourth order $a$, that is

$$b = -a$$

If we set the offset of the input image at 1/2, and set the size of the image at 1, then the maximum wavefront aberration in the image is ±a/8, whereas if the image can be placed on the optical axis, the wavefront aberration becomes ±a/128, that is, it can be reduced by a factor of 16.

Equation (1) indicates that all the operation requires is to take the Fourier transform of two input images and add the transformed functions in the Fourier plane. In this sense, it is not necessary to take Fourier transform by one lens. We therefor propose a modified version of the optical system for the joint transform correlator. Figure 2 shows a schematic diagram of the new design. In this system, two separate lenses transform the images on the input planes, and the results by both lenses fall on the BSO crystal. As mentioned, the aberration is reduced by a
4. Influence of Crystal Thickness

Another problem of the optical system is caused by the angular selectivity of thick holographic recording material. Though precise analysis of the influence of the crystal thickness have been reported,\textsuperscript{4,4} we make here a simple approximation in which the reference image is assumed to be small. In this case, the influence of the thick recording material becomes similar to the reconstruction of a volume hologram. The intensity of the diffracted correlation pattern \( I(x) \) is weighted by the square of a sinc function, i.e.,

\[
I(x) \propto \text{sinc}^2 \left( \frac{hD}{n\lambda f^2} x \right),
\]

where \( x \) is the coordinate in the correlation plane, \( D \) is the thickness of the crystal, \( f \) is the focal length of the transform lens, \( h \) is the offset of the images in the input plane, \( \lambda \) is the wavelength and \( n \) is the refractive index of the crystal.

For a temporal criterion to reduce this effect, we set the size of the correlation plane \( L_c \) smaller than the width of the sinc function, that is

\[
L_c < \frac{n\lambda f^2}{hD}.
\]

Then, we have the following relation for the focal length of the transform lens.

\[
f > \sqrt{\frac{DhL_c}{n\lambda}}.
\]

In the optical system shown in Fig. 2, the offset of the image \( h \) corresponds to the product of the focal length of the transform lens and half of the angle \( \alpha \), the angle between the two object beams.

In our experiments, the thickness of the crystal \( D \) was 3 mm, the refractive index \( n \) of BSO was 2.65, \( \lambda \) was 0.515 \( \mu \text{m} \), the size of the correlation plane \( L_c \) and the offset \( h \) were 25 mm, so that the focal length of the transform lens \( f \) should be larger than 1.2 m. Since the correlator's length must be four times of the focal length, it becomes as long as 5 m. A large optical system, however, tends to be influenced by air turbulence, and to become heavy.

So, we propose a technique to reduce the size of the correlator by employing magnification optics to lengthen the focal length effectively. There are two ways to magnify the Fourier plane. One is by using a concave lens,\textsuperscript{4,4} and the other is by using a convex lens. In general, it is not easy to get a well-corrected concave lens, but it is easy to get a convex lens, because such lenses are used for microscope objectives. Thus, using a convex lens seems more practical, and we adopted this configuration for the experiments.

5. New Design of the Optical Correlator and Experimental Results

Figure 3 shows a schematic diagram of the optical joint transform correlator used for the experiments. The unknown object and the reference images are displayed separately on liquid crystal spatial light modulators (SLM's) and transformed by two Fourier transform lenses, \( L_a \) and \( L_4 \), with focal lengths of 200 mm and diameters of 50 mm. The transformed patterns are superposed on the Fourier plane and magnified by a microscope objective lens. We set the magnification ratio at 15, so that the effective focal length became 3 m, and this value fulfilled the above mentioned condition.

A half mirror combines the light beam from a He-Ne laser to the transformed pattern, and it illuminates the crystal. The lens \( L_a \) just behind the crystal compensates the quadratic phase factor introduced by the magnification lens, and the diffracted light by the BSO crystal is demagnified and transformed by lenses \( L_4 \) and \( L_a \) to make the correlation pattern on a CCD camera.

A small computer controls the entire system, i.e., taking
setting tolerance is determined by the spot size of the transform lens. Larger aperture and shorter focal length of this lens causes smaller tolerance, and this fact would restrict the size of the input images.

Figure 4(a) shows the object and the reference images used for an experiment, in which five images of characters are arranged in a vertical column and five references in a horizontal column. The correlation of these images has five by five peaks, each corresponding to the correlation depicted in Fig. 4(b). Figure 4(c) shows the result of the correlation. Five bright auto-correlation peaks are shown in the photograph with some dimmer cross correlation peaks.

Figure 5 shows the case of half tone images: (a) shows the object and the reference images, and (b) shows the resultant correlation, in which a strong correlation peak can be recognized one of the reference images corresponding to the object image.

6. Conclusion

A new configuration of an optical joint transform correlator is presented. Employment of two transform lenses minimizes lens aberration, and use of a magnification lens allows realization of a compact optical system. Experimental results show that the correlator recognizes objects in real time from a set of reference images. The main advantage of this system is flexibility in the reference images, which enables us to compare an object to various images sequentially.

For future work, we are considering making this system
flexible for scale change and orientation of an object. One means of doing this is to take advantage of the system's real time operation feature, changing the scale and the orientation of objects and/or references until the brightest correlation peak.

Acknowledgments

Part of this research was supported by a Grant-in-Aid for Scientific Research on Priority Areas, from the Ministry of Education, Science and Culture of Japan.

References