Optical Correlation with Light of Tunable Wavelength

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A novel method is described for compensation of size variations in the input pattern of an optical correlator for pattern recognition by appropriate adjustment of the reconstruction wavelength. Simple ring-shaped patterns of variable diameter have been optically cross-correlated. Using a tunable dye laser of narrow bandwidth, the correlator output was analyzed for various combinations of size and wavelength to show the performance of the method.

Introduction

Optical correlation employing holographic filters in the spatial frequency plane has been used for various applications in pattern recognition [1]. For this purpose the Fourier transformed input signal illuminates a Fourier transform hologram of the pattern to be recognized. A second transformation yields, among other terms, the cross-correlation product of the two signals, which may be used for subsequent recognition analysis. Both transformations are performed with lenses of equal focal length f resulting in a length $4f$ of the correlator (Vander Lugt filtering [2]) as shown in Figure 1a. Despite the elegance of this method, its practical application suffers from some severe restrictions which have prevented it from general use. Among these is the sensitivity of the cross-correlation output to small distortions in the pattern like changes in size. In the present paper this size effect is studied in detail and a method is introduced which compensates for the change in size by change of the reconstruction wavelength. A tunable cw dye laser is used as coherent light source of adjustable wavelength and bandwidth. It is shown that the original cross-correlation function can be easily restored thus producing the signal wanted for detection. The detuning of the laser wavelength from pattern to pattern provides a measure for the size variations.

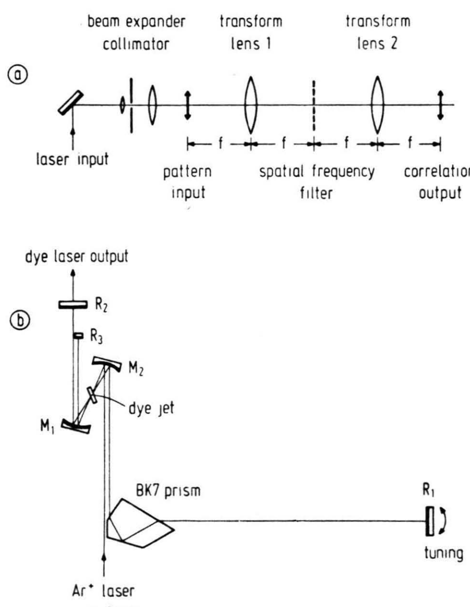

Fig. 1. a) Schematic of setup for optical correlation. b) Schematic of tunable dye laser used for optical correlation. Dye laser mirrors R_1, R_2, and R_3 flat and concave mirrors M_1 and M_2 of 100 mm radius of curvature.

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Theoretical Background

The basic relation permitting optical filtering is the Fourier transform relationship between the transmittance $f(x,y)$ of an optical pattern and its far-field diffraction characteristic. When the pattern is placed at a distance of one focal length f in front of a collective lens, the light amplitude in the back focal plane is given by the Fourier transform:

$$F_\lambda(u,v) = \int\int_{-\infty}^{+\infty} f(x,y) \cdot \exp\left[-2\pi i\left(\frac{u}{\lambda\cdot f}x + \frac{v}{\lambda\cdot f}y\right)\right] dx\, dy \tag{1}$$

with u, v denoting the coordinates in the spatial frequency plane parallel to x, y and λ being the wavelength of the light.

Assume now a change in size of the original pattern by a factor α, i.e. $f_\alpha(x,y) = f(x/\alpha, y/\alpha)$. Introducing this into Eq. (1) yields the spatial frequency spectrum of the altered signal

$$F_{\alpha\lambda}(u,v) = \alpha^2 \cdot F_\lambda(\alpha u, \alpha v) . \qquad (2)$$

This expresses the well-known fact that a spectrum grows wider as the signal narrows. Similarily, a change in wavelength from λ_0 to λ yields

$$F_\lambda(u, v) = F_{\lambda_0}[u\,\lambda_0/\lambda, v\,\lambda_0/\lambda] \qquad (3)$$

showing that a change in size is equivalent to a change in wavelength from λ_0 to λ_0/α, disregarding the constant factor α^2. Thus a size factor α can be compensated by a wavelength $\lambda = \alpha\,\lambda_0$. This basic relation can be employed in operating an optical correlator for recognition of patterns of different size. Actually, a rigorous formulation of the exact theory requires a little more effort, since the method involves reconstruction of a holographic filter with a wave different in shape and wavelength from the waves used in recording the hologram. The problem will be treated in detail in a forthcoming paper [3].

Experimental Results

To study the effect of pattern size and wavelength on the correlation output, a very simple pattern was used: a circular ring, representing the letter "0". This pattern has the advantage that the correlation output is insensitive to misadjustments in orientation which could influence the size effects to be studied.

The input patterns were produced by photographic reproduction of drawings made by a computer-driven plotter of high accuracy. Since all the patterns were photographed with exactly the same setting, their relative scale was known from the plotter instruction. All holographic filters were produced at the He-Ne laser wavelength of $\lambda_0 = 632.8$ nm, which all wavelength and size data had to be referred to.

To demonstrate the sensitivity of the optical correlation technique to size changes, input patterns of different size were correlated using a filter made with a pattern of fixed size. The illuminating light was of constant wavelength $\lambda_0 = 632.8$ nm. Figure 2 illustrates some results giving the central peak of the correlator output which is surrounded by a rather weak ring at a distance of twice the pattern radius not shown here. The deviation of this peak from a clear bright spot to a ring-shaped structure is shown as a consequence of gradual change in size of the input pattern. Changes in size by only a few percent completely smear out the correlation peak, so that a detecting device at the position of the center peak would no longer produce any reliable signal. As a matter of fact, quite soon the center even turns completely dark.

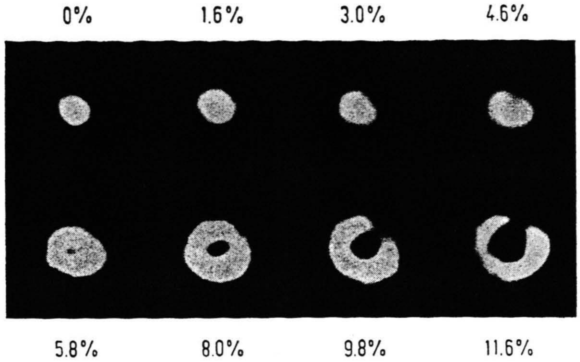

Fig. 2. Central maximum of optically produced cross-correlation of ring patterns of variable size. The percent difference in size of the two rings is indicated. Illuminating light $\lambda_0 = 632.8$ nm.

In a second series of experiments input signal and filter were kept constant while the wavelength was tuned. Thus the He-Ne laser was substituted by the tunable, narrowband cw dye laser shown in Figure

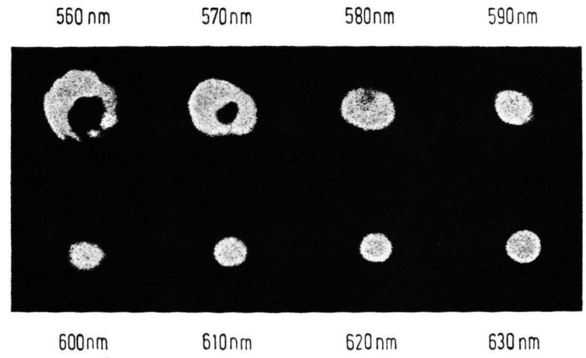

Fig. 3 Central maximum of optically produced cross-correlation of two ring patterns. The holographic filter was recorded of a pattern of relative size 1.0 at $\lambda_0 = 632.8$ nm. The correlation was made with a pattern of relative size 0.9735 at different wavelengths which are indicated. Autocorrelation is expected at $\lambda = 616$ nm.

1 b. The laser construction is based on a Kogelnik-type folded cavity [4] with small alterations as to off-axis pumping [5] and introduction of a z-shaped pumping geometry to facilitate output coupling with mirror R_2. The dye laser could be conveniently tuned by rotation of mirror R_1 without any lateral displacement of the output beam. The setup allowed an overall tuning range of 70 nm (560 nm to 630 nm) at a constant output power of 2 mW, using a $1 \cdot 10^{-3}$ molar solution of rhodamine 6 G in ethylene glycol in a free flowing dye sheet. The emission wavelength of the laser was measured with a prism spectrograph and the bandwidth was monitored with an analyzing Fabry-Perot etalon, indicating a multi-mode bandwidth of less than 1 Å.

Figure 3 shows the effect of wavelength tuning on the shape of the central peak of the cross-correlation output. Since in this case the filter was produced at 632.8 nm for a pattern of relative size 1.0, while the input signal for the experiment was of relative size 0.9735, a wavelength of 616 nm compensates for the difference in size. The picture series clearly indicates that the small relative variations of the wavelength lead to appropriate changes in the shape of the cross-correlation center.

An evaluation of the cross-correlation functions thus obtained and their comparison with theoretical predictions is planned [3]. Thus it should be possible to comment on the applicability of these optical techniques for quantitative correlation. There are several possible regions of potential use of the method. It can, for example, be applied in automatic quality control to classify single pieces of variable size when a rapidly tunable dye laser [6, 7] is used.

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