Extended scale-invariant pattern recognition with white-light illumination

José J. Esteve-Taboada, Javier García, and Carlos Ferreira

A previous method of obtaining scale-invariance detection with white-light illumination has been improved on. We were able to detect different scaled versions of the target up to a magnification factor equal to 2. We simultaneously detected several versions in the same scene, because each scale factor is codified in a different wavelength. Experimental results demonstrate the proposed technique and show the utility of the method. © 2000 Optical Society of America

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1. Introduction

Scale invariance is an important issue in the field of pattern recognition. The first attempts to obtain scale invariance in an optical system did not maintain the shift invariance present in the classical matched filter.[1] In this way Casasent and Psaltis[2] achieved scale invariance through a Mellin transform and a logarithmic coordinate transform, at the cost of renouncing the shift invariance. Later, Mendlovic *et al*.[3] obtained shift and scale invariance by use of Mellin radial harmonics. This method was enhanced afterward by Rosen and Shamir,[4] who achieved scale invariance, using logarithmic radial harmonics. Recently, Cojoc *et al*.[5] achieved recognition of objects within a limited scale range by means of radial stretching of a phase-only filter (POF),[6] depending on the cumulative angular distribution of the energy of the target spectrum. They obtained results comparable with those obtained by use of the method reported in Ref. 4, and they increased the performances of the filters described in Ref. 3, yielding similar correlation-peak heights corresponding to scaled targets.

Nevertheless, all the optical methods cited previously were implemented with temporal coherent light (a laser beam, for instance). This allows for optical systems to perform many image processing operations in real time. However, the processing capabilities of these systems are limited, owing to the coherent artifact noise, which Gabor[7] noted to be the number one enemy in optical processing systems. Consequently, there has been extensive interest in carrying out optical processing operations with temporally incoherent illumination (spectrally broadband light source). The use of incoherent light allows for reduction of the inevitable coherent artifact noise that limits the capabilities of coherent systems. Thus many authors have developed methods to accomplish with incoherent light operations that earlier had been restricted to the use of coherent light.

In that way one brilliant development in the white-light optical processing field was the study of Morris and George.[8] They combined a holographic matched filter and an achromatic-fringe interferometer to perform an optical correlator that works with spectrally broadband light sources. They used a compensating grating to eliminate the lateral chromatic dispersion in the correlation signal from the VanderLugt filter. Afterward, Mersereau and Morris[9] achieved scale, rotation, and shift-invariant image recognition in the system described by Morris and George years before. However, concerning scale invariance, the system was limited to the case in which the object magnification factor was smaller than or equal to 1.25.

Other approaches have used the different wavelengths to obtain other invariances, such as rotation invariance,[10] or, in general, to multiplex different channels.[11] In this sense the Morris and George setup multiplexes the different scales of the object at different wavelengths.

On the basis of the compensation approach we introduce an enhanced system. First, we employed a

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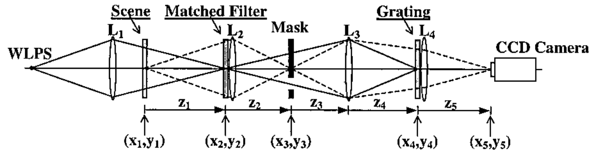

Fig. 1. Sketch of the experimental optical setup.

POF in a VanderLugt correlator. This filter provides a much greater discrimination ability than does the matched filter.[6] The use of a double carrier frequency for the hologram allows for a wide input image to be processed. Further improvement of the discrimination of the filter, although at the price of losing light efficiency and the rigorous behavior as a POF, can be achieved by application of high-pass filtering by modification of the filter with a central stop. Second, we enlarged the object magnification factor such that the system gives a correlation peak extending our detection rank from the visible to the near-infrared (NIR) electromagnetic spectrum. Thus we achieved scale-invariant detection for a magnification factor smaller than or equal to 2. This is possible by use of a monochromatic CCD camera, which has an inherent response also in the NIR spectrum. Finally, we used, as an input object, a scene composed of various targets to be recognized. We showed with this same scene the detection of scaled versions of the target with the above-mentioned rank for the magnification factor.

In Section 2 we analyze the optical setup and its basic theory. In Section 3 optical experiments show the utility of the method introduced here. Finally, the main conclusions are outlined.

2. Basic Theory of the System

The optical setup is sketched in Fig. 1. The symbols are defined in the figure. It can be divided into two parts: The first one, the front part up to the plane (x_3, y_3), is a classical VanderLugt correlator,[1] in which the input scene is described by the function $s(x_1, y_1)$ and the matched filter is adapted to the target $t(x_1, y_1)$. The mask at plane (x_3, y_3) selects only the term corresponding to the correlation between the input scene and the target, smeared according to the wavelength. So at this plane, when illuminating with light of wavelength λ, we have (except for constant factors)

$$U(x_3, y_3; \lambda) = \left[t\left(\frac{\lambda_0 z_0 x_3}{\lambda z_2}, \frac{\lambda_0 z_0 y_3}{\lambda z_2}\right) \star s\left(\frac{z_1 x_3}{z_2}, \frac{z_1 y_3}{z_2}\right)\right] \otimes \delta(x_3, y_3 - \alpha\lambda z_2), \tag{1}$$

where the symbol $\star$ denotes the cross-correlation operation and the symbol $\otimes$ denotes the convolution operation. We have assumed that the filter matched to the target $t(x_1, y_1)$ is recorded in the usual way with light of wavelength λ_0 and with a plane wave incident at an angle θ as reference beam, so the carrier frequency is $\alpha = (\sin\theta/\lambda_0)$.

If the system is illuminated with a white-light point source (WLPS), following Eq. (1) it can be seen that at plane (x_3, y_3) the lateral position of the correlation term is linearly proportional to the wavelength of the illumination beam. Thus the second part of the setup sketched in Fig. 1 is a system that compensates the chromatic dispersion that appears in the correlation plane. Following with the mathematical analysis of the system, lens L_3 provides at plane (x_4, y_4) an image of the part corresponding to the correlations at plane (x_2, y_2). When we denote by M the magnification introduced by the lens, the field distribution at plane (x_4, y_4) is given by

$$U(x_4, y_4; \lambda) = \tilde{t}^*\left(\frac{x_4}{\lambda_0 z_0 M}, \frac{y_4}{\lambda_0 z_0 M}\right)\tilde{s}\left(\frac{x_4}{\lambda z_1 M}, \frac{y_4}{\lambda z_1 M}\right) \times \exp\left(-i2\pi\alpha\frac{y_4}{M}\right). \tag{2}$$

It can be seen that the chromatic dispersion is due to the exponential factor in this equation. Placing a grating with the suitable period in this plane, we can eliminate this chromatic dispersion and obtain all the correlation terms at the same transversal position independently of the wavelength of illumination λ. If we denote the period of the compensating grating by p, it must be equal to

$$p = \frac{M}{\alpha} = \frac{-z_4\lambda_0}{(z_2 + z_3)\sin\theta}. \tag{3}$$

Taking into account the compensating grating, we can write the field distribution at plane (x_4, y_4) as

$$\begin{aligned} U(x_4, y_4; \lambda) &= \tilde{t}^*\left(\frac{x_4}{\lambda_0 z_0 M}, \frac{y_4}{\lambda_0 z_0 M}\right)\tilde{s}\left(\frac{x_4}{\lambda z_1 M}, \frac{y_4}{\lambda z_1 M}\right) \\ &\quad\times \exp\left(-i2\pi\alpha\frac{y_4}{M}\right)\sum_{n=-\infty}^{+\infty}\exp\left(i2\pi n\alpha\frac{y_4}{M}\right) \\ &= \tilde{t}^*\left(\frac{x_4}{\lambda_0 z_0 M}, \frac{y_4}{\lambda_0 z_0 M}\right)\tilde{s}\left(\frac{x_4}{\lambda z_1 M}, \frac{y_4}{\lambda z_1 M}\right) \\ &\quad\times \sum_{n=-\infty}^{+\infty}\exp\left[i2\pi(n-1)\alpha\frac{y_4}{M}\right]. \end{aligned} \tag{4}$$

Then, performing the final Fourier transform with lens L_4, we can write the field distribution at plane (x_5, y_5) as

$$\begin{aligned} U(x_5, y_5; \lambda) = \sum_{n=-\infty}^{+\infty}&\left[t\left(\frac{\lambda_0 z_0 M x_5}{\lambda z_5}, \frac{\lambda_0 z_0 M y_5}{\lambda z_5}\right)\right. \\ &\left.\star\, s\left(\frac{z_1 M x_5}{z_5}, \frac{z_1 M y_5}{z_5}\right)\right] \\ &\otimes\, \delta\left[x_5, y_5 - \frac{(n-1)\alpha\lambda z_5}{M}\right]. \end{aligned} \tag{5}$$

We have many dispersion terms that contain the correlation between the scene and the target, but only the term with $n = 1$ does not present chromatic dispersion. For the other orders the delta function term will produce a smeared correlation for every wavelength. In addition, the $n = 1$ term is centered with the optical axis, owing to the position of the correlation term at plane (x_3, y_3). Then, considering the term with $n = 1$ and introducing the new variables $x_5' = (Mx_5/z_5)$ and $y_5' = (My_5/z_5)$, we have

$$U_{n=1}(x_5', y_5'; \lambda) = t\left(\frac{\lambda_0 z_0 x_5'}{\lambda}, \frac{\lambda_0 z_0 y_5'}{\lambda}\right) \star s(z_1 x_5', z_1 y_5'). \tag{6}$$

Now we can see how the system works to be scale invariant. If in the input scene we have a scaled version of the target, for instance, $s(x, y) = t(x/m, y/m)$, we have a correlation peak at plane (x_3, y_3) for the wavelength of the spectrally broadband light that fulfills [see Eq. (6)]

$$\lambda = \lambda_0 z_0 m / z_1. \tag{7}$$

Thus, if we assume $z_0 = z_1$, the wavelength that gives the correlation peak is linearly proportional to the scale factor of the input scene. That is, each scaled version of the target is detected with a correlation peak of different wavelength.

Taking into account that our white-light spectrum goes from $\lambda = 400$ nm to $\lambda = 800$ nm (visible + NIR electromagnetic field), and considering that we have chosen $\lambda_0 = 600$ nm, we obtain a correlation peak for the scaled versions of the target [see Eq. (7)] if m belongs to the interval [2/3, 4/3]. So we can detect targets scaled with a magnification factor smaller or equal to 2. Another choice for the value of λ_0 (always inside of the interval considered for λ) does not change the magnification factor rank (always equal to 2), as can be seen easily following Eq. (7).

3. Experimental Results

In this section we show the experimental results obtained with the system sketched in Fig. 1. The lenses in the arrangement are as follows: L_1 is a 300-mm focal length achromatic doublet; L_2 and L_3 are achromatic photographic lenses of 150- and 135-mm focal length, respectively; and L_4 is a 180-mm focal length achromatic doublet. The distances z_2, z_3, and z_4 are set to the appropriate values that fulfill $|M| = 1$.

The input scene is shown in Fig. 2. It is composed of different scaled versions of the B, G, and X characters. We matched the POF to the central version of the G character, which has scaling factor $m = 1$. The other versions of the G character have scaling factors $m = 2/3$, 3/4, and 4/3. The POF is recorded as a binary computer-generated hologram calculated with the Lohmann detour phase method[12] in 256 × 256 cells with a resolution of 17 × 17 pixels/cell and is plotted with a 600-dot/in. laser printer. The filter was then photoreduced to a size of 10 mm × 10 mm on a lithographic film. The compensating grating [which will be placed in the plane (x_4, y_4)] was recorded following the same steps, with a final frequency equal to that of the hologram of the POF. We employed a 250-W xenon lamp as the broadband source. The light from this lamp was focused onto a pinhole to form the WLPS. We used a Pulnix Model TM-765 CCD camera to grab the experimental output at plane (x_5, y_5).

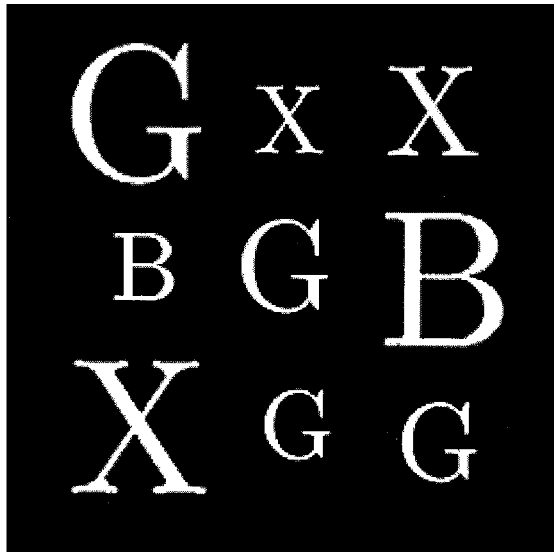

Fig. 2. Input scene composed of different scaled versions of the B, G, and X characters.

Figure 3 shows the chromatically compensated correlation output obtained in the CCD. We can observe four correlation peaks that point out the presence of the different scaled versions of the G character. Each peak is obtained for the corresponding value of the wavelength obtained from Eq. (7); i.e., the color of each peak indicates the scale factor of the character detected. Thus the peak denoted with letter (a) is a dark-blue one that points out the presence of the G character with $m = 2/3$. The (b) peak is a green one that indicates the presence of the G character with $m = 3/4$. And the (c) peak is a

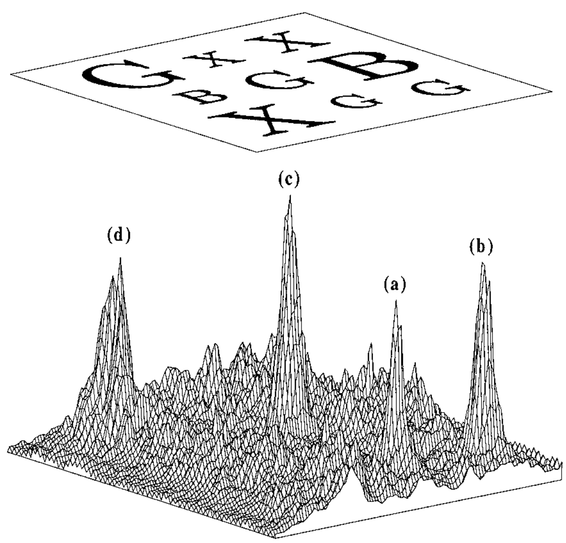

Fig. 3. Chromatically compensated correlation output obtained in the CCD camera. Each correlation peak indicates the presence of a different scaled version of the G character.

light-red one that points the presence of the G character with $m = 1$. Finally, the peak denoted with letter (d) corresponds to the detection of the G character that has a scale factor $m = 4/3$. In accordance with Eq. (7), this peak appears at a wavelength that belongs to the NIR spectrum. Thus, even though the lenses we used are chromatically compensated, this good correction applies only for the visible spectrum, so the NIR peak has a different axial position. Thus in Fig. 3 this peak is a little defocused. This can be avoided by use of lenses chromatically compensated from the visible to the NIR. However, we can detect the presence of the four versions of the G character with a thresholding value equal to 44% of the maximum correlation peak.

In addition, in our case it is easy to prove that, for a detection of a character with scale factor m, the intensity of the correlation peak is proportional to $1/m^2$. Nevertheless, this fact is not perceptible in Fig. 3, because it is partially compensated with the WLPS spectral emission and the CCD spectral response. The joint effect of the CCD and the WLPS responses produces a total correlation response that is roughly constant for the visible spectrum and for the NIR spectrum.

4. Conclusions

In conclusion, we have improved on a previous method of obtaining scale-invariance detection with white-light illumination up to a magnification factor equal to 2. Moreover, we are able to simultaneously detect different scaled targets in a scene, because each scale factor is codified in a different wavelength belonging to the visible and the NIR electromagnetic spectrum.

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