Optical recognition of three-dimensional objects with scale invariance using a classical convergent correlator

José J. Esteve-Taboada
Javier García
Carlos Ferreira
Universitat de València
Facultat de Física
Departament Interuniversitari d'Òptica
C/Doctor Moliner 50
46100 Burjassot
València, Spain
E-mail: jose.j.esteve@uv.es

Abstract. We present a real-time method for recognizing three-dimensional (3-D) objects with scale invariance. The 3-D information of the objects is codified in deformed fringe patterns using the Fourier transform profilometry technique and is correlated using a classical convergent correlator. The scale invariance property is achieved using two different approaches: the Mellin radial harmonic decomposition and the logarithmic radial harmonic filter. Thus, the method is invariant for changes in the scale of the 3-D target within a defined interval of scale factors. Experimental results show the utility of the proposed method.
 [DOI: 10.1117/1.1476326]

Subject terms: optical pattern recognition; correlators; three-dimesional object recognition.

Paper 010244 received July 16, 2001; revised manuscript received Dec. 5, 2001; accepted for publication Dec. 10, 2001.

1 Introduction

Recognition of three-dimensional (3-D) objects is an increasingly important issue in the field of optical pattern recognition. However, most of the existing methods for pattern recognition using optical setups, such as the VanderLugt optical correlator[1] and the joint transform correlator[2] (JTC), have been devoted to the recognition of bidimensional (2-D) objects. Although these optical correlators are invariant only to the lateral shifts of the input object, other invariant properties, such as target in-plane rotation invariance or target scale invariance, can be obtained by use of harmonic decompositions, in which the input object is decomposed into a set of harmonic functions and the reference function is chosen as a single expansion order, or by use of specifically designed filters in the Fourier plane. Within the first approach, circular harmonics[3] and Mellin radial harmonics[4] (MRHs) are used to obtain rotation-invariant and 2-D scale invariant pattern recognition, respectively. In the second approach, for instance, the logarithmic radial harmonic (LRH) filter[5] and the elliptically coordinate-transformed filter[6,7] are both used to obtain 2-D scale invariance.

There are applications, however, in which the necessary information is not contained in just one 2-D projection of the target, but in all its 3-D shape. In these applications, a full 3-D treatment is required. Much recent research has been developed to the task of optically recognizing 3-D objects. A first possibility is to use optical or digital processing over a range image.[8,9] The main drawback of this setup is the need for a range camera, which is not easily available. A different approach uses a JTC architecture combined with electronic processing of the images obtained from several cameras.[10,11] This is a complex setup and requires considerable amount of digital calculation. However, it is demonstrated that it provides localization of the 3-D target in the 3-D space. Other techniques are based on digital holography as a method for recording 3-D information.[12–14] They are based on correlating the planar holograms of the 3-D functions. From a practical point of view, these procedures have the difficulty that a hologram from a 3-D rough object is determined by the microscopic structure of the object surface, thus producing a low correlation for two similar 3-D objects that have a different microscopic structures.

Recently, a real-time optical technique for the recognition of 3-D objects was proposed.[15] This method is based on using the Fourier transform profilometry (FTP) technique[16] to introduce the 3-D information of the object into the system. The FTP technique relies on projecting a grating onto the surface of a 3-D object and capturing the resultant 2-D image, which is a deformed fringe pattern that carries all the 3-D information of the object. As demonstrated in Ref. 15, the analysis of such patterns is the basis of the method for recognizing 3-D objects.

In this paper, we propose a system that enables optical scale-invariant 3-D object recognition. The method is based on using the FTP technique in a classical convergent correlator. The scale-invariance property is achieved by two different approaches: the MRH decomposition and the LRH filter.

Section 2 reviews the main aspects of the 3-D object recognition method introduced in Ref. 15 that are relevant for our purposes. Section 3 reviews the definition and the most important properties of the MRH decomposition and the LRH filter for scale-invariant pattern recognition. Section 4 presents a description of the method and the experimental setup. Section 5 introduced both simulated results and optical experiments showing the performance of our method. Finally, Sec. 6 outlines the main conclusions.

2 Three-Dimensional Object Recognition

The FTP technique[16] is used to obtain an image of a 3-D object. It is based on projecting a grating on the object's surface and capturing the resultant 2-D image with a camera. If the axes of the projector and the camera are not coincident, we obtain a distorted fringe pattern that codifies all the 3-D information of the object. In our experiment, we employ the parallel-axes geometry, in which the optical axes of the projector and the camera lie in the same plane and are parallel. As is explained in Ref. 15, for a general 3-D object with varying $h(x,y)$, the distorted grating pattern can be described by

$$s(x,y)=r(x,y)\sum_{n=-\infty}^{\infty} A_n \exp\{in[\phi(x,y)+2\pi f_0 x]\}, \quad (1)$$

where f_0 is the fundamental frequency of the observed grating image, and $r(x,y)$ is the reflectivity distribution on the object surface [$r(x,y)$ is zero outside the object extent]. The function $\phi(x,y)$ contains all the information about the 3-D shape since the connection between $\phi(x,y)$ and the height of the object $h(x,y)$ can be written as

$$\phi(x,y)=\frac{-2\pi f_0 d h(x,y)}{L-h(x,y)}, \quad (2)$$

where d is the distance between the projector and the camera, and L is the distance between the camera and the object. In particular, if $L \gg h(x,y)$, it is clear that the phase is just proportional to the height of the object.

This phase function, which contains all the 3-D information of the object, can be digitally obtained (as is explained in Ref. 15) by selecting only the first order of the 2-D Fourier transform (FT) of the distorted grating pattern and performing an inverse 2-D FT of the centered result. This enables us to obtain a complex function for which phase is just the function $\phi(x,y)$, while the amplitude is directly proportional to the reflectivity of the object. Therefore we are able to encode the 3-D object in a complex image. Here we call this complex image the phase-encoded height function (PEHF).

The 3-D object recognition can be obtained by encoding the 3-D input objects into PEHFs and correlating them. This idea can be implemented using a modified JTC, as shown in Ref. 15, and also using a classical convergent correlator,[17] as we show in Sec. 4.

3 Scale-Invariant Pattern Recognition

3.1 *MRH Decomposition*

Any object function expressed in polar coordinates can be expanded into a set of orthogonal functions called the MRH as follows:

$$f(r,\theta;x_0,y_0)=\sum_{M=-\infty}^{+\infty} f_M(\theta;x_0,y_0)\, r^{i2\pi M-1}, \quad (3)$$

with

$$f_M(\theta;x_0,y_0)=\frac{1}{L}\int_r^R f(r,\theta;x_0,y_0)\, r^{-i2\pi M-1} r\,\mathrm{d}r, \quad (4)$$

where R is the maximum radius of the object, L is an integer, $r=R\exp(-L)$ is the smallest radius considered in the expansion, M is the expansion order, and (x_0,y_0) is the Cartesian coordinate origin of the (r,θ) polar coordinates. Although the definition of MRHs treats M as an integer, the expansion order can be also extended, without loss of the orthogonality, to any fractional value. In the following, for the sake of simplicity, the coordinates of the origin (x_0,y_0) will be used only when necessary.

If we consider a filter matched to only one MRH component of order M of the given object and any other pattern represented by $g(r,\theta)$ as the input in a correlator, the complex amplitude in the center of the correlation plane is given by

$$C_{f,g}=\frac{1}{L}\int_r^R\int_0^{2\pi} g(r,\theta) f_M^*(\theta)\, r^{-i2\pi M-1} r\,\mathrm{d}r\,\mathrm{d}\theta, \quad (5)$$

where the asterisk denotes complex conjugation.

In particular, if $g(r,\theta)$ is equal to the function $f(r,\theta)$, the complex amplitude in the center of the correlation peak results

$$\begin{aligned} C_{f,f}&=\frac{1}{L}\int_r^R\int_0^{2\pi} f(r,\theta) f_M^*(\theta)\, r^{-i2\pi M-1}\, r\,\mathrm{d}r\,\mathrm{d}\theta \\ &=\frac{1}{L}\int_r^R\int_0^{2\pi}\sum_{N=-\infty}^{+\infty} f_N(\theta)\, r^{i2\pi N-1} f_M^*(\theta) \\ &\quad\times r^{-i2\pi M-1} r\,\mathrm{d}r\,\mathrm{d}\theta. \end{aligned} \quad (6)$$

Taking into account the orthogonality properties of the MRH decomposition,[4] Eq. (6) yields

$$\begin{aligned} C_{f,f}&=\frac{1}{L}\int_r^R\int_0^{2\pi} f_M(\theta)\, r^{-1} f_M^*(\theta)\,\mathrm{d}r\,\mathrm{d}\theta \\ &=\int_0^{2\pi} f_M(\theta) f_M^*(\theta)\mathrm{d}\theta. \end{aligned} \quad (7)$$

Consider now that the function $g(r,\theta)$ in Eq. (5) is a scaled version (with a scale factor β) of the function $f(r,\theta)$. Of course, it can be decomposed into MRHs as follows:

$$\begin{aligned} g(r,\theta)&=f\left(\frac{r}{\beta},\theta\right) \\ &=\sum_{N=-\infty}^{+\infty} f_N(\theta)\left(\frac{r}{\beta}\right)^{i2\pi N-1} \\ &=\frac{\beta}{\exp[i2\pi N\ln(\beta)]}\sum_{N=-\infty}^{+\infty} f_N(\theta)\, r^{i2\pi N-1}. \end{aligned} \quad (8)$$

Substituting this expression in Eq. (5), and taking into account again the orthogonality properties of the MRHs, the complex amplitude in the center of the correlation peak results

$$C_{f,f}^{\beta}=\frac{\beta}{\exp[i2\pi M\ln(\beta)]}\int_0^{2\pi} f_M(\theta) f_M^*(\theta)\,\mathrm{d}\theta. \tag{9}$$

Comparing Eq. (7) and Eq. (9) one can obtain

$$C_{f,f}^{\beta}=\frac{\beta}{\exp[i2\pi M\ln(\beta)]}C_{ff}. \tag{10}$$

Thus, the relation between the intensity of the correlation peaks can be written as

$$|C_{f,f}^{\beta}|^2=\beta^2|C_{f,f}|^2. \tag{11}$$

That is, when we scale the input patterns, the relative correlation intensity remains unaffected when comparing with the relative intensity of the input scaled functions.

When using MRHs to obtain scale-invariant pattern recognition, it is very important to carefully select the expansion order and the expansion center of the MRH component of the target used to build the filter. In Ref. 18, an algorithm to obtain the most suitable order and the proper center of the decomposition into MRH's of any function $f(r,\theta;x_0,y_0)$ is presented. The algorithm is based on the construction and later maximization of a modified energy function of the target. The modification in the energy function consists of the suppression of the nondiscriminant uniform background. This method, which we used later, is an automatic and selective technique to calculate the optimum parameters that optimize the discrimination ability of the system.

3.2 *LRH Filter*

Given an input object function $f(r,\theta)$ and its scaled version with factor β, $f(\beta r,\theta)$ (both expressed in polar coordinates considering the same origin for simplicity), the relation between their FTs can be written as

$$G(\rho,\phi)=\frac{1}{\beta^2}F\left(\frac{\rho}{\beta},\phi\right), \tag{12}$$

where $F(\rho,\phi)$ and $G(\rho,\phi)$ are the FTs of the functions $f(r,\theta)$ and $f(\beta r,\theta)$, respectively. This equation indicates that the FT of a scaled function is proportional to the scaled FT of the original function. Rosen and Shamir[5] used this property to define a new filter in the Fourier plane of an optical correlator that enabled scale-invariant pattern recognition. The general structure of the filter is $H(\rho,\phi)=R(\rho)S(\phi)$. Considering the input object function $f(r,\theta)$ in an optical system with this filter in its Fourier plane, the value of the obtained correlation center can be written as

$$C_{f,h}=\int_d^D\int_0^{2\pi}F(\rho,\phi)R^*(\rho)S^*(\phi)\rho\,\mathrm{d}\rho\,\mathrm{d}\phi, \tag{13}$$

where D is the maximum radius of the filter, d is the radius of a high-pass filter, and the asterisk denotes a complex conjugate. If we consider the input object function as a scaled version $f(\beta r,\theta)$ of the original one, the correlation center value can be expressed as

$$C_{f,h}^{\beta}=\int_{d/\beta}^{D/\beta}\int_0^{2\pi}F(\tau,\phi)R^*(\beta\tau)S^*(\phi)\tau\,\mathrm{d}\tau\,\mathrm{d}\phi, \tag{14}$$

where the parameter τ denotes ρ/β.

To have a scale-invariant filter, the relation between these two last equations must be

$$C_{f,h}^{\beta}=C_{f,h}\exp[i\sigma(\beta)], \tag{15}$$

where $\sigma(\beta)$ is a real function depending only on the scale factor β. This condition enables us to define the scale-invariant filter, known as a phase-only LRH filter, as[5]

$$H^*(\rho,\phi)=\exp[i\Omega(\phi)]\left(\frac{\rho}{d}\right)^{i(p/w)}, \tag{16}$$

where p is the LRH frequency, w is a normalization constant defined by

$$w=\frac{1}{2\pi}\ln\left(\frac{D}{d}\right), \tag{17}$$

and $\Omega(\phi)$ is an angular phase function that caries all the angular information contained in the phase of the object function

$$\Omega(\phi)=-\arg\left[\int_d^D F(\rho,\phi)\left(\frac{\rho}{d}\right)^{i(p/w)}\rho\,\mathrm{d}\rho\right]. \tag{18}$$

Thus, the correlation value $C_{f,h}^{\beta}$ yields

$$C_{f,h;p}^{\beta}=\left(\frac{\beta}{d}\right)^{i(p/w)}\int_0^{2\pi}\exp[i\Omega(\phi)]\times\left[\int_{d/\beta}^{D/\beta}F(\tau,\phi)\tau^{i(p/w)}\tau\,\mathrm{d}\tau\right]\mathrm{d}\phi, \tag{19}$$

and in the particular case in which the scale factor $\beta=1$,

$$|C_{f,h;p}^{1}|=\int_0^{2\pi}\left|\int_d^D F(\tau,\phi)\tau^{i(p/w)}\tau\,\mathrm{d}\tau\right|\mathrm{d}\phi. \tag{20}$$

As can be seen comparing these two last equations, the expression of Eq. (19) satisfies exactly the relation of Eq. (15) only when the scale factor $\beta=1$. In any other case, as is explained in Ref. 5, the relation of Eq. (15) is accomplished approximately for a certain scale range because of the β dependence on the integration limits. In addition, the correlation depends on the LRH frequency p, which must be properly chosen to optimize the behavior of the filter.

4 Description of the Method

The experimental setup is sketched in Fig. 1. It can be separated into the acquisition part and the processing part.

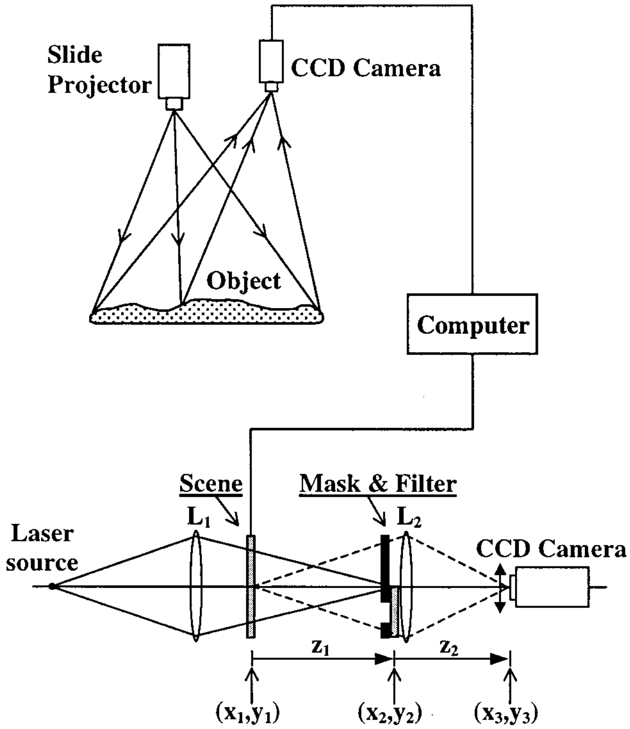


Fig. 1 Optical arrangement including the acquisition part and the correlation process. In the optical correlator, the CCD camera must be moved out from the optical axis to capture the correlation output.

The acquisition part, composed of the slide projector and the CCD camera, enables us to obtain all the information of the 3-D objects codified in distorted grating patterns following the FTP technique. The slide projector images a regular grating pattern onto the surface of the 3-D objects, and the resultant 2-D distorted fringe patterns are captured with the CCD camera. The processing part is a classical convergent correlator that allows for obtaining at plane (x_3,y_3) the correlation between the considered functions.

As stated, 3-D object recognition can be obtained by encoding the 3-D input objects into PEHFs and correlating them. To achieve the scale invariance property, MRH target decomposition or LRH filter are used. The first step to build the filter placed at plane (x_2,y_2) is to obtain the PEHF of the target, which is the function that carries all its 3-D information in the phase. As explained in Sec. 2, this process is done digitally. Once we have the PEHF of the target we can choose its proper MRH expansion order to match the filter, or directly build an LRH filter from this PEHF. It is important to note that the function taken to build the filter is just the PEHF corresponding to the 3-D target, because this is the function that contains all the necessary 3-D information to perform the recognition process.

The input scene (see Fig. 2), composed of several distorted grating patterns, is introduced in the correlator using a spatial light modulator (SLM). At plane (x_2,y_2) we obtain optically the 2-D FT of these distorted patterns, which is a set of diffraction orders each one separated from another by the carrier frequency f_0. In the first order, which is nothing but the inverse FT of the corresponding PEHFs, we codified the height information of the 3-D objects. We use a mask to select only this first order, and we place in the same plane the filter properly centered (see Fig. 1). This enables us to obtain in the final plane the correlation between the PEHFs of the 3-D objects (distorted patterns of which were placed in the input scene) and the inverse FT of the filter made from the 3-D target.

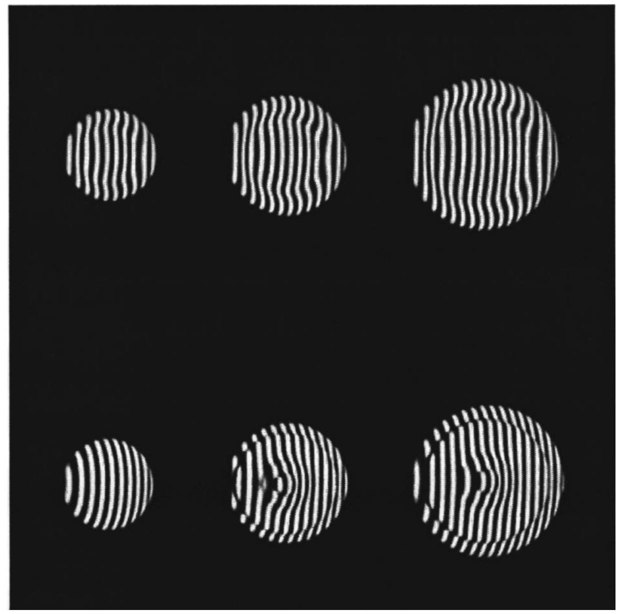


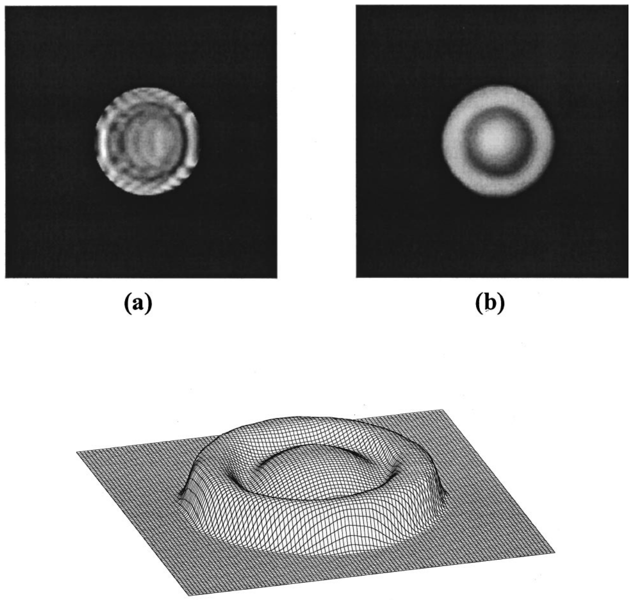
Fig. 2 Input scene used to test the scale-invariant 3-D object recognition ability of the system.

To achieve a high SNR in the correlation plane it is very important to carefully place the filter centered over the first diffraction order. This can be done by using a micrometric positioner in the (x_2,y_2) plane. Note that, as the position of this first order depends only on the carrier frequency of the distorted patterns, the proper position of the filter will be the same while the period of the distorted grating patterns in the input scene remains unchanged.

5 Simulated Results and Optical Experiments

The input scene (shown in Fig. 2) is composed of several images that are the deformed fringe patterns obtained when a grating is projected onto the surface of the 3-D objects (several small doorknobs). In the upper part, there are three different scaled versions of the target, with scale factors equal to 0.75, 1.00, and 1.25. In the lower part there are the false 3-D objects used to demonstrate the discrimination ability of the system.

First, we consider the MRH decomposition to achieve the scale-invariance property in the 3-D object recognition process. In a first stage previous to perform the correlation we obtain the PEHF from the target with scale factor equal to 1.00. The modulus and the phase of this PEHF, which was obtained digitally as already explained, are shown in Figs. 3(a) and 3(b). Figure 3(c) shows a perspective view of the phase part, which is directly proportional to the height of the 3-D object. From this PEHF, the MRH component of expansion order $M=0.9$ is computed by taking as polar coordinate origin the center of the image. These are the optimal values calculated using the algorithm presented in Ref. 18. The parameter L, which takes into account the relation between the maximum and minimum radii consid-



(a) (b)

(c)

Fig. 3 (a) Amplitude and (b) phase of the PEHF that corresponds to the 3-D target and (c) perspective view of the phase of this PEHF. As we can see, it is directly proportional to the height of the 3-D target.

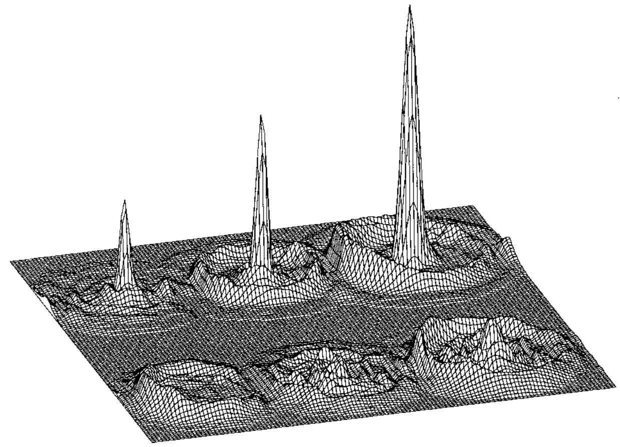


Fig. 4 Simulated result obtained for the input scene shown in Fig. 2 when a filter matched to a MRH component of the PEHF of the 3-D target is used.

ered in the calculation of the MRH component, is chosen to be 4, with the maximum radius being equal to the maximum size of the object. Once we have the MRH component, the filter is obtained by computing the complex conjugate of its 2-D FT. Then, the filter is recorded as a binary computer-generated hologram (CGH) calculated with the Lohmann detour phase method[19] in 256×256 cells with a resolution of 17×17 pixels/cell, and is plotted with a 600-dots/in. laser printer. Such a filter was photoreduced to a size of 10×10 mm on a lithographic film to place it at plane (x_2,y_2).

Just before the filter in the plane (x_2,y_2) a mask is used to filter the FT of the scene and select only the first order. By centering the considered filter over this first order we can obtain in the final plane of the system a correlation between the PEHFs of the 3-D objects in the input scene and the inverse FT of the filter, that is, the MRH component of the PEHF corresponding to the target.

The simulated correlation plane is shown in Fig. 4. The three correlation peaks correspond to each one of the different scaled 3-D targets placed in the input scene. Thus, we are able to recognize and detect the 3-D target independently of its scale factor, in a range of scales equal to 1.67. However, as already shown, the energy of the correlation peak is directly proportional to the square of the scale factor of the target. This is the main drawback of the MRH decomposition: the detection is scale invariant in the sense that the relative intensity distribution of the correlation functions remains constant. Even so, the three objects can be detected at the same time by using an appropriate threshold in the intensity of the correlation plane.

The usefulness of the proposed method was also tested by optical experiments. The experimental correlation result, obtained with the system sketched in Fig. 1 and grabbed with a Pulnix TM-765 CCD camera, is shown in Fig. 5. As we can seen, the high similarity between the experimental and the simulated results demonstrates the good performance of the experimental optical setup.

To solve the dependence on the scale factor on the energy of the correlation peak, instead of the MRH decomposition, we can use the LRH filter to obtain the 3-D object recognition with the scale-invariance property. Thus, from the PEHF that corresponds to the target with scale factor 1.00 we compute the LRH filter using as polar coordinate origin the center of the image. The only parameter to be optimized in the designing of the filter is just the LRH frequency p. We have chosen the value 2.3, which is the one that maximizes the peak-to-correlation energy for the three different scaled targets placed in the input scene. Then, the LRH filter is recorded as a binary CGH and photoreduced in the same way as the MRH matched filter. Also, this obtained LRH filter is placed over the masked first order of the 2-D FT of the input scene at plane (x_2,y_2).

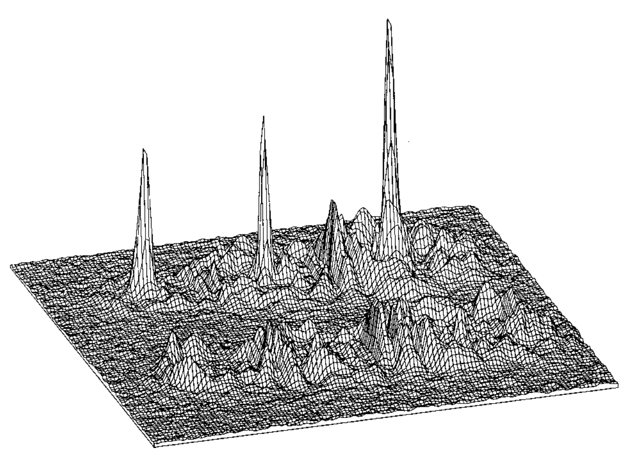


Fig. 5 Experimental correlation obtained for the input scene shown in Fig. 2 when a filter matched to a MRH component of the PEHF of the 3-D target is used. Note the high similarity between the simulated and the optical results.

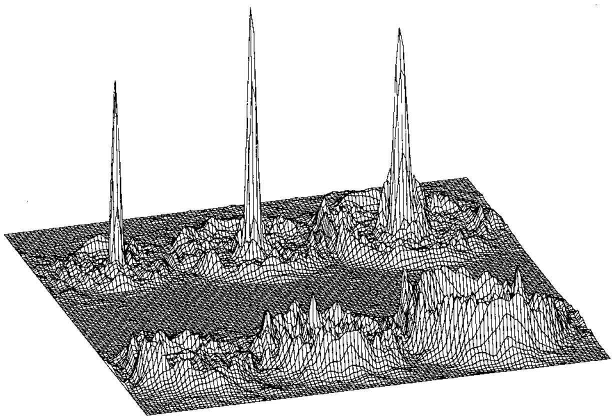


Fig. 6 Simulated result obtained for the input scene shown in Fig. 2 when a LRH filter obtained from the PEHF of the 3-D target is used.

The simulated correlation plane and the experimental result are shown in Figs. 6 and 7, respectively.[20] We obtain three correlation peaks, each one corresponding to each different scaled 3-D target placed in the input scene, enabling a clear discrimination with the other correlation terms that appear in the lower part of the image owing to the false 3-D objects. Now the three correlation peaks have almost the same energy (the small difference for the central peak is due to the fact that the LRH filter is calculated from the PEHF that corresponds to the central 3-D target). Thus, it is possible to recognize 3-D objects with scale invariance using the LRH filter.

As shown, both the MRH decomposition and the LRH filter can provide detection of all the targets at the same time by using an appropriate threshold in the correlation plane. The suitable threshold should be taken between two values corresponding, on one hand, to ensure that all the false alarms are rejected (low threshold, LT), and on the other hand, to ensure that all the targets are detected (high threshold, HT). Therefore, the LT is calculated as the ratio, in percent, between the maximum intensities of the false alarms and the targets, respectively. In the same way, the HT is obtained as the ratio between the minimum and the maximum intensities corresponding to the targets. In our case, considering the optical results, for the MRH decomposition the suitable threshold should be within the interval $[\mathrm{LT,HT}]=[26.0,69.7]\%$. For the LRH filter, the threshold should be within [31.1, 88.6] %. Thereby, in a typical situation with no *a priori* knowledge of the scene, the possibility of choosing a correct threshold is higher for the LRH filter.

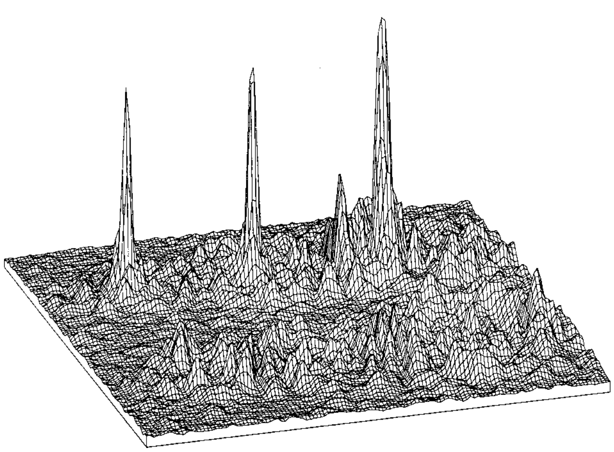


Fig. 7 Experimental correlation obtained for the input scene shown in Fig. 2 when a LRH filter obtained from the PEHF of the 3-D target is used.

Note that if the camera and the slide projector are far from the 3-D object, i.e., $L \gg h(x,y)$, the phase $\phi(x,y)$ is directly proportional to the height of the object [see Eq. (2)]. Then the experimental setup sketched in Fig. 1 is also invariant to shifts along the direction given by $h(x,y)$ (see Ref. 15) within a limited interval of depth positions. This enables detection that is invariant under displacements on the three axes and under changes in the scale of the target. It is clear that the shift invariance along the line of sight has a different nature than the transversal shift invariance, since the correlation peak follows the transverse shift of the target, but stays at the same point when it changes its depth position.

Finally, note that our method has some inherent limitations, mainly derived from the FTP technique. One of the most important limitations is the limited interval of depth positions in which the invariance along the line of sight can be obtained (which limits, in fact, the inspection volume). This limitation comes from two factors. First, the depth of focus of both the projector and the camera, which can be overcome by using, for example, an interference system for generating the grating. And second, the dependence on L (distance between the object and the projector) in the function $\phi(x,y)$ that carries information about the shape of the 3-D object [see Eq. (2)]. This dependence will introduce significant changes in the PEHFs of the shifted objects (when comparing with the PEHF of the target encoded in the filter), which will decrease the correlation signal.

6 Conclusions

A method for achieving scale-invariant 3-D object recognition was presented. It is based on encoding the 3-D information of the objects in 2-D distorted grating patterns using the FTP technique. The scale-invariance property was achieved by two different approaches: the MRH decomposition and the LRH filter. In a first step, simulated results demonstrated the good operation of the method.

The proposed method was also optically implemented using a classical convergent correlator. The filter was obtained from the PEHF of the 3-D target, and is conveniently centered at the masked Fourier plane. Experimental results verify the theory and show the utility of the method here introduced. The convergent correlator inherits from linear correlation the shift-invariance property. Moreover, as stated, under certain conditions our setup is also invariant to shifts along the direction given by the height of the object. The robustness and the simplicity of the optical setup are in contrast with other procedures of 3-D object recognition.

The whole proposed experimental setup can be constructed with simple equipment and, except for the first computation of the filters, electronic or digital processing are not required, so the system can operate at nearly video rates.

Possible applications of our system are in the field of automatic vision, such as classification, testing, and tracking of 3-D objects.

Acknowledgments

José J. Esteve-Taboada acknowledges a grant from the Conselleria de Cultura, Educació i Ciència (Generalitat Valenciana). The authors thank the Spanish Ministerio de Ciencia y Tecnología (project BFM2001-3004) and the DGR of the Generalitat de Catalunya (project XT99-0014) for financial support.

References

1. A. VanderLugt, ''Signal detection by complex spatial filtering,'' *IEEE Trans. Inf. Theory* **IT-10**, 139–145 (1964).
2. C. S. Weaver and J. W. Goodman, ''A technique for optically convolving two functions,'' *Appl. Opt.* **5**(7), 1248–1249 (1966).
3. Y. N. Hsu and H. H. Arsenault, ''Optical pattern recognition using circular harmonic expansion,'' *Appl. Opt.* **21**(22), 4016–4019 (1982).
4. D. Mendlovic, E. Marom, and N. Konforti, ''Shift and scale invariant pattern recognition using Mellin radial harmonics,'' *Opt. Commun.* **67**, 172–176 (1988).
5. J. Rosen and J. Shamir, ''Scale invariant pattern recognition with logarithmic radial harmonic filters,'' *Appl. Opt.* **28**(2), 240–244 (1989).
6. J. García, T. Szoplik, and C. Ferreira, ''Shift-and-scale-invariant pattern recognition using elliptic coordinate-transformed phase-only filter,'' *Appl. Opt.* **31**(23), 4823–4828 (1992).
7. D. Cojoc, M. T. Molina, J. García, and C. Ferreira, ''Coordinate-transformed filter for shift-invariant and scale-invariant pattern recognition,'' *Appl. Opt.* **36**(20), 4812–4815 (1997).
8. E. Paquet, M. Rioux, and H. H. Arsenault, ''Invariant pattern recognition for range images using the phase Fourier transform and a neural network,'' *Opt. Eng.* **34**, 1178–1183 (1995).
9. E. Paquet, P. García-Martínez, and J. García, ''Tridimensional invariant correlation based on phase-coded and sine-coded range images,'' *J. Opt.* **29**, 35–39 (1998).
10. J. Rosen, ''Three-dimensional electro-optical correlation,'' *J. Opt. Soc. Am. A* **15**(2), 430–436 (1998).
11. J. Rosen, ''Three-dimensional joint transform correlator,'' *Appl. Opt.* **37**(32), 7538–7544 (1998).
12. T. Poon and T. Kim, ''Optical image recognition of three-dimensional objects,'' *Appl. Opt.* **38**(2), 370–381 (1999).
13. T. Kim and T. Poon, ''Extraction of 3-D location of matched 3-D object using power fringe-adjusted filtering and Wigner analysis,'' *Opt. Eng.* **38**, 2176–2183 (1999).
14. B. Javidi and E. Tajahuerce, ''Three-dimensional object recognition by use of digital holography,'' *Opt. Lett.* **25**(9), 610–612 (2000).
15. J. J. Esteve-Taboada, D. Mas, and J. García, ''Three-dimensional object recognition by Fourier transform profilometry,'' *Appl. Opt.* **38**(22), 4760–4765 (1999).
16. M. Takeda and K. Mutoh, ''Fourier transform profilometry for the automatic measurement of 3-D object shapes,'' *Appl. Opt.* **22**(24), 3977–3882 (1983).
17. J. W. Goodman, *Introduction to Fourier Optics*, 2nd ed., Electrical Engineering Series, McGraw-Hill, Singapore (1996).
18. A. Moya, E. Tajahuerce, J. García, D. Mendlovic, and C. Ferreira, ''Method for determining the proper expansion center and order for Mellin radial harmonic filters,'' *Opt. Commun.* **103**, 39–45 (1993).
19. A. W. Lohmann and D. P. Paris, ''Binary Fraunhofer holograms generated by computer,'' *Appl. Opt.* **6**(10), 1739–1748 (1967).
20. C. Ferreira, J. J. Esteve-Taboada, and J. Garcia, ''Three-dimensional pattern recognition using fringe projection,'' in *Wave Optics and VLSI Photonic Devices for Information Processing*, P. Ambs, Ed., *Proc. SPIE* **4435**, 31–41 (2001).

José J. Esteve-Taboada received his MS degree in physics from the University of Valencia, Spain, in 1998 and has since been preparing his doctoral thesis in the Optics Department. He had a research stay with the Ecole Nationale Supérieure de Physique de Marseille, France, working on problems related to detection of objects in the three-dimensional (3-D) space. His current research includes optical pattern recognition, linear and nonlinear image processing, 3-D object recognition, and wavelength multiplexing. He is a member of OSA.

Biographies and photographs of other authors not available.