PSEUDOCOLORING METHOD FOR 3-D CONTOURING

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MOTS CLÉS : Speckle Contour

SUMMARY : The interference properties of white light speckle pattern obtained with an optical system not corrected for chromatic aberration are applied to pseudocolor encode the depth level contours of a 3-D diffusing object. At a first step, a recording of the different encoded images of depth levels is done. In a second step, a reconstructed pseudocolored image is obtained, where different color assignments can be tuned by changing the position of a spatial filter slit. Also, a quantitative contouring can be made scanning the pseudocolored image plane with a spectroscopic device.

INTRODUCTION

Speckle patterns produced by partially coherent white light have been theoretically and experimentally studied in the last few years [1]. Namely, the statistical properties of white light speckle have been investigated in the image plane [2-6] and in the diffraction field [7, 8]. The dependence of the speckle pattern contrast with surface roughness was established in connection with different parameters that characterize the optical system and the illuminating light: the amplitude point spread function, and the spatial and temporal coherences. K. Nakagawa and T. Asakura [9] have shown experimentally that the average contrast of the white light image speckle depends strongly on the surface roughness: for small values of r.m.s. roughness (lower than 0.5 μm) the relevant parameter is the spatial coherence, while for large values of r.m.s. roughness the effect of the point spread function is more important. When the speckle pattern is observed at a defocused plane, for an object roughness greater than 1 μm, the additional phase-noise distortion produced by defocusing does not affect much the speckle pattern contrast. On the other hand, for surface objects having a r.m.s. roughness lower than 0.3 μm, the speckle pattern contrast is affected by the phase-noise distortion due to defocusing [7].

In the present study, the interference properties of white light patterns are applied to pseudocolor encode depth level contours of a 3-D object. For this purpose, an optical imaging system affected by chromatic aberration with an exit pupil consisting in two identical slits, is employed. In this way, the white light speckle pattern results in pairs of tiny spectra. When both spectra of each pair intersect they do it for the same wavelength and interference Young’s fringes appear in the intersection region. Therefore, at a fixed distance from the imaging lens, for each object plane there exists a coded image for a certain wavelength. This spatial codification of color information is decoded, in a further step, to obtain a depth level pseudocoloring of the 3-D object. On the other hand, if the rough surface is a plane one, a study of the chromatic aberration of the optical system can be done.
GENERAL CONSIDERATIONS

When a rough plane surface is illuminated by partially coherent quasi-monochromatic light, the speckle intensity distribution in the diffraction and image planes is given by

\[ I(x') = \int \int \Gamma(x_1, x_2) K(x' - x_1) K^*(x' - x_2) O(x_1) O^*(x_2) \, dx_1 \, dx_2 \]

where \( \Gamma(x_1, x_2) \) is the spatial coherence function between two different object points \( x_1 \) and \( x_2 \) that characterizes the quasi-monochromatic illuminating light; \( K(x) \) is the amplitude point spread function of the optical system; and \( O(x) \) is the complex amplitude of the object. For simplicity, only a one dimensional analysis is done. Taking into account the intensity fluctuations due to random phase changes introduced by the surface roughness, the above expression (1) results

\[ \langle I(x') \rangle = \int \int \Gamma(x_1, x_2) K(x' - x_1) K^*(x' - x_2) \langle O(x_1) O^*(x_2) \rangle \, dx_1 \, dx_2 \]

where \( \langle \cdots \rangle \) indicates ensemble average. The speckle pattern contrast can be defined as: \( V = \langle \Delta I^2 \rangle^{1/2}/\langle I \rangle \). Therefore it should be noted that it depends on the surface roughness, the coherence conditions of the illuminating light, and the employed optical system.

When white light is used, and the optical imaging system is not corrected for chromatic aberration, different image planes appear, each one corresponding to a different color. In this way, taking into account the dispersion constant of the lens, a continuous variation of focused and defocused speckle patterns occurs. At each image plane, the amplitude point spread function \( K(x) \) determines the variation of the speckle pattern contrast with wavelength, in accordance with relation (2). Therefore, using a slit as lens aperture, the resulting polychromatic speckle pattern, at a certain observation plane, consists of tiny spectra. In this case, each quasi-monochromatic speckle pattern can be treated by the general expression (2).

In this paper the interference conditions of these spectra, when a two-aperture pupil is used, are applied to obtain a mapping of depth level contours. When such a system is employed the image of a 3-D diffusing object consists of pairs of intersecting tiny spectra. Therefore, the intersection region exhibits Young's fringes, the spatial frequency of which is determined by the temporal frequency of the corresponding color. Because this intersection temporal frequency \( v \) is fixed by the specific function \( n = n(\lambda) \) that describes the chromatic aberration of the lens, as \( v \) takes all values of the visible spectrum, different planes are characterized for a given fixed image plane. Thus, a pseudocolor encoding of level contours of a 3-D object can be obtained.

DESCRIPTION OF THE METHOD

In the method we present here, the optical system consists of a white light source \( S_0 \) limited by a diaphragme \( D \), an achromatic lens \( L_1 \), and a second lens \( L_2 \) not corrected for chromatic aberration whose pupil consists of two laterally displaced slits \( R_1 \) and \( R_2 \) symmetrically located to the optical axis of the system. This arrangement is shown in figure 1. For a given \( \lambda \) characterizing a certain band of the spectra, the amplitude point spread function \( K(x', y') \), at the image plane, is the smallest spread diffraction pattern of one slit modulated itself by Young's fringes. Namely,

\[ (3) \quad K_d(x', y'; \lambda) = f(x', y'; \lambda) \left[ 1 + \cos \left( \frac{2\pi x'}{p} + \phi \right) \right] \]

where \( f(x', y'; \lambda) \) takes into account the slit diffraction pattern at the image plane corresponding to \( \lambda \)-wavelength; \( p = d/\lambda z_0 \) is the spatial frequency of Young's fringes; and \( \phi \) is a constant phase delay. Because of the chromatic aberration of the employed optical system, the image point spread function for each \( \lambda \) lies in a different plane in accordance with the relationship: \( n = n(\lambda) \).

Thus, for a given object distance \( z_0 \), the image distance \( z(\lambda) \) for each \( K_d(x', y'; \lambda) \) results

\[ z(\lambda) = \frac{C z_0}{z_0 [n(\lambda) - 1] - C} \]

where \( 1/C \) is the geometrical bending parameter that characterizes the lens \( L_d \).

The white light speckle pattern of a plane diffusing object is observed at a fixed plane \( \pi \), such that the image point spread functions \( K_d(x', y'; \lambda) \), corresponding to several wavelengths \( \lambda \), lie in planes near \( \pi \). In this way, only for a color represented by a certain wavelength \( \lambda^{(0)} \), \( K_d(x', y'; \lambda^{(0)}) \) lies in the \( \pi \)-plane. For all other wavelengths \( \lambda \), the point spread functions \( K_d(x', y'; \lambda) \) are broader than \( K_d(x', y'; \lambda^{(0)}) \) in the \( \pi \)-plane. Therefore, an expression of \( K_d(x', y'; \lambda) \) can be given as

\[ K_d(x', y'; \lambda) = f_d(x', y'; \lambda) \left[ 1 + \gamma [z(\lambda)] \cos \left( \frac{2\pi x'}{p} + \phi \right) \right] \]

where \( f_d(x', y'; \lambda) \) takes into account the slit diffraction pattern at the defocused plane \( \pi \). The attenuation factor \( \gamma [z(\lambda)] \) of Young's fringes is originated by...
the limited spatial coherence of the light source $S_0$. Neglecting Young's fringes with visibility values lower than the corresponding to the condition:

$$K(x; \Delta z_i) = 0, \quad \text{for } x > L_c,$$

the attenuation factor $\gamma[z(x_c)]$ may be assumed as

$$\gamma[\Delta z_i] = 1 - \frac{|\Delta z_i|}{\alpha}.$$  \hspace{1cm} (4)

In the above expressions, $L_c$ denotes the spatial coherence length (which is determined by the Van Cittert-Zernike theorem), and $\Delta z_i$ is the distance between the $\pi$-plane and the image plane associated with $\hat{x}$. Assuming a geometrical behavior of $K(x; \Delta z_i)$, an expression for $\alpha$ can be given as

$$\alpha = mL_c \frac{z_0(x_{c0})}{d}.$$  

where $m$ is the longitudinal magnification, $d$ is the separation between $R_1$ and $R_2$, and $z_0(x_{c0})$ is the object distance of the $\pi$-plane. Therefore, for a certain image plane such that

$$z(x_{c0}) - \alpha > z(x_{c0}) > z(x_{c0}) + \alpha, \gamma(\Delta z_i) \simeq 0,$$

Fig. 1. — Schematic diagram of the experimental set-up used in the registering step. Due to chromatic aberrations, $\Pi_3$ conjugates $\pi$-plane and its surroundings (which are shown in detail in the lower part of the figure) with $\pi'$-plane.

Fig. 2. — Schematic diagram of the experimental set-up employed in the decoding step. $P$ represents the output plane.
PSEUDOCOLOR ENCODING OF DEPTH LEVELS

As we stated above, a pseudocolored image of the 3-D object is obtained employing a second lens behind the spatial filter slit \( R_4 \). Nevertheless, it is possible to carry out a preliminary real time visualization using the optical arrangement shown in figure 1. The color of the Young's fringes associated with the several image planes acts as a primary tool to evaluate the depth level contours of the object, and it can be observed with a microscope focused in the \( \pi \)-plane. In figure 3 is shown the polychromatic speckle pattern where Young's fringes appear only for green color.

When a recording of this speckle pattern is done, the spectral range of the pseudocolored reconstructed image is determined by the spectral band of the image planes that are focused on the photographic plate. The different color encoding planes are related by,

\[
\sin \theta = \frac{\lambda_0}{\lambda_r} \frac{d}{z_i}
\]

where \( \theta \) is the angular position of \( R_4 \), \( \lambda_0 \) is the observation wavelength, and \( \lambda_r \) is the recording wavelength. In this way, changing the value of \( \theta \) it is possible to tune the chromatic interval, so that the colors originally focused on the photographic plate appear in the pseudocolored image. Other false colors, ruled by the expression (7), can be selected in the coded image. Therefore, it is possible to obtain a pseudocolored image in the spectral range where better human eye color discrimination occurs. Besides, if a spectroscopic device is used such that the input slit is placed in the plane of the reconstructed pseudocolored image, the contouring of the 3-D object, in the input slit direction, is displayed in the output plane of the analyzer device. In this case, the profile of the 3-D surface can be obtained scanning the pseudocolored image with the slit of the spectroscopic device, and with appropriate calibration a quantitative contouring can be made.
In figure 4 and 5, experimental results are shown corresponding to an object composed of two plane rough surfaces, one of which is normal to the optical axis, and the other one lies in a tilted and axially shifted plane. The angle of tilt was 3°, and the shift was of 2 mm. Both photographs were taken for two different positions of the spatial filter slit \( R_4 \). In this way, two different pseudocolored images of the same object are obtained. The optical frequency difference \( \Delta \nu \), corresponding to the colors associated with each plane, is,

\[
\Delta \nu = v_2 - v_1 = k \sin \theta
\]

where \( k \) is a constant given by \( k = c (1/A_2 - 1/A_1) \); \( c \) is the vacuum light velocity; \( A_2 \) and \( A_1 \) are the spacings of Young's fringes corresponding to each plane. Therefore, a greater chromatic difference is obtained by placing the slit \( R_4 \) in the region of shorter wavelengths.

3-D RECONSTRUCTION CAPABILITY

As it has been pointed out before (Eq. (7)), the reconstructed image can be obtained with the same colors that were properly focused on \( H \) in the registering step. If \( H \) is replaced in its original location and the reconstruction is done as it is indicated in figure 6, light rays actually travel the inverse path. In this way, a 3-D image of +1 magnification of the original object can be obtained in its original position. In this case geometrical aberrations are cancelled. Nevertheless, due to the presence of a narrow slit, depth of field is large and resolution is severely limited. Because of this, the 3-D nature of the images is difficult to observe experimentally. At present, we are intending to overcome these shortcomings.

The pictures shown in figure 4 and 5 were actually obtained in this way, and a slight misfocusing can be observed in the left side of the images.

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**Fig. 4. — Experimental result.**

**Fig. 5. — Experimental result.**

**Fig. 6. — Schematic diagram of the experimental set-up employed for 3-D reconstruction.**

\( O\!A_1 \): optical axis of the achromatic transforming lens \( L_1 \), centered at \( R_2 \) slit position. \( O\!A_2 \): optical axis of the not corrected lens \( L_2 \). \( M \): mask to block the undesired « 0 order ». 
CONCLUSIONS

In this paper we have applied the interference properties of white light speckle pattern obtained with an optical system not corrected for chromatic aberration to pseudocolor encode the depth level contours of a 3-D diffusing object. Due to the special optical arrangement employed the resulting polychromatic speckle pattern consists of tiny spectra with a spatial fringe modulation determined by the optical frequency corresponding to the intersection of spectra. In this way, a spatial encoding of an object-space determined by the amount of axial chromatic aberration of the optical system, is accomplished. In a further step, a pseudocolored image is obtained through a temporal-spatial filtering operation.

This method allows the false colors to be tuned; i.e. varying the location of the slit $R_4$ is possible to select different color assignments. In this way, any particular zone of interest of the object can be tuned in order to be shown in the color of maximal human eye discrimination. Also, in the case of a continuous variation of depth, a continuous color encoding is obtained. However, the useful volume is small as it is limited by the amount of axial chromatic aberration. Because of the finite size of the involved slits, image resolution is limited in one direction.

Alternatively, if a plane rough surface is used as object, both the axial chromatic aberration and the lateral chromatic aberration may be studied.

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Pseudocoloring method using two different spatial modulations

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Pseudocoloring of gray level information is a technique for introducing false colors in a black-and-white transparency. The importance of this operation is based on the human eye’s ability to distinguish different colors better than gray levels. In the last few years several pseudocoloring optical methods have been proposed.\(^1\)\(^-\)\(^1\)\(^0\) Furthermore, the pseudocoloring technique has been extended to encode image spatial spectral bands\(^1\)\(^1\)\(^-\)\(^1\)\(^3\) and holographic interferometric fringe patterns.\(^1\)\(^4\)

In a recent paper\(^1\)\(^5\) we presented a further generalization of pseudocoloring for assigning false colors to depth level contours of 3-D objects.

In this Letter we propose a modification of the pseudocoloring speckle method\(^9\) for storing two images in a single recording material in such a way that each recorded image has a different spatial modulation. Therefore, in a decoding step, on illuminating the processed plate with a white light source, there exist two wavelength values for which the spatial spectra of both encoded images are centered at the same spatial frequency value. Thus, an additive mixture of both images is produced with a pseudocoloring effect which depends on the two mentioned wavelengths.

The scheme of the optical arrangement utilized in the encoding step is shown in Fig. 1. The image of a certain scene \(E_1\) is recorded by using as a lens pupil a double aperture of separation \(d_1\). This causes a spatial spectra shift \(\Delta \nu_1\) given by \(\Delta \nu_1 = \frac{d_1}{\lambda D}\), where \(\lambda\) is the light wavelength, and \(D\) is the image distance.\(^6\) Afterward, a record of the image of another scene \(E_2\) is done in the same plate but now using as a lens pupil a double aperture of separation \(d_2\). Thus, the spatial spectra shift \(\Delta \nu_2\) is given by \(\Delta \nu_2 = \frac{d_2}{\lambda D}\).

The decoding step is shown in Fig. 2. The developed plate \(H\) is illuminated with a collimated white light beam. Then, for a certain value of the viewing angle \(\theta\), there exist a superposition of the \(E_1\) and \(E_2\) images in the colors given by the corresponding wavelengths \(\lambda_1\) and \(\lambda_2\) such that \(\frac{d_2}{d_1} = \frac{\lambda_1}{\lambda_2}\). In this way, all the common parts of the \(E_1\) and \(E_2\) images are pseudocolored by a color mixture which depends on \(\lambda_1\) and \(\lambda_2\).

So far no relation exists between \(E_1\) and \(E_2\). However, if \(E_1\) and \(E_2\) images are complementary (for object transparencies, the positive and negative images), the image resulting from the superposition is a pseudocolored one of either \(E_1\) or \(E_2\). The corresponding contrast reversed image can be obtained employing the method of Ref. 10, that is, recording the light scattered from the silver developed grains that form the original image transparency. An alternative approach consists of employing the optical subtraction technique through Young's fringes modulated speckle.\(^1\)\(^6\) In this case, a first record of the image of a speckle pattern is made. Then the image of the same speckle pattern is recorded but modulated by the object transparency \(E_1\), introducing a \(\pi\)-phase delay between both exposures. Thus, a contrast reversed image of \(E_1\) is obtained. Another case of interest arises when the image of \(E_2\), instead of being the complementary one of \(E_1\), is a modified version of it. In this case, the third pseudocolor encodes the common regions of both scenes. Some experiments have been done using as \(E_1\) the isochromatic fringe pattern that appears in a loaded photoelastic model. The scene \(E_2\) corresponds to the complementary fringe pattern (obtained by rotating the polarization state of the incident light by 90°) but with a different loading condition. Therefore, in the decoding step, the resulting moire pattern appears in a pseudocolor given by the mixture of \(\lambda_1\) and \(\lambda_2\).

Finally, another point of interest for this pseudocolor encoding consists of studying the spatial changes in one direction of an object transparency. In this case, the \(E_2\) image is a shifted version of the \(E_1\) image. The amount of shifting depends on the size of the finest details to be studied. Thus, the sign of the gray level change is coded by a spectral color which corresponds to \(\lambda_1\) or \(\lambda_2\).

In summary, we have presented a simple method for generalizing the speckle pseudocoloring technique to include other cases besides gray level pseudocoloring. An advantage of this method consists of employing colors, given by \(\lambda_1\) and \(\lambda_2\), that are spectral. When using green and red as false colors, as usual, it is possible with this method to obtain a third color which lies in a straight line in the chromatic diagram, very close to the locus of the spectral colors. In this way, false colors of high purity are obtained.

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