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Investigation of an image processing method of step-index multimode fiber specklegram and its application on lateral displacement sensing

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ABSTRACT

An image processing algorithm named gray level co-occurrence matrix (GLCM) is introduced to improve the fiber specklegram sensors applied to displacement sensing. The GLCM algorithm is used to analyze the Fourier phase spectra of step-index multimode fiber (MMF) specklegrams. Approximately linear relations between the GLCM features and the lateral displacement between the launching SMF and the MMF have been obtained, which indicate the capability of lateral displacement sensing by GLCM analysis of the specklegrams. Experimental results show that lateral displacement detection can be realized by MMFs with a wide range of parameters and the method exhibits better performance than the conventional NIPC (normalized intensity inner product coefficient) method.

1. Introduction

When laser radiation is launched into an optical multimode fiber (MMF), a complex speckle pattern appears at the output end of the fiber, which is known as a specklegram. The specklegram results from the modal interference in the MMF. Since the spatial and temporal characteristics of the speckle field are affected by the light guidance conditions, the specklegram can be used to quantify the physical status of MMF, and has been widely used in fiber sensing [1–4]. Besides, due to the wavelength dependence, specklegrams have also been used in optical spectra analysis [5,6]. Considering the randomness of the speckle pattern, the specklegrams have found applications in compressive image disposing and secret communications as well [7,8].

In these applications, several methods have been proposed to measure the speckle variation. One type is based on the intensity evaluation, among which one commonly used method is based on the calculation of the normalized intensity inner product coefficient (NIPC) of specklegrams [9,10], the NIPC decreases as the speckle pattern deviates from the reference one, making it possible to quantify the relative variations in fiber status. However, because this approach relies on the evaluation of the phase change, if the perturbation of the sensing fiber becomes extremely severe, Ref. [9] has shown that the NIPC will reduce to a constant value. Thus, it inevitably presents limitations regarding the dynamic range. Mean absolute speckle intensity variation method has also been used, the same restrictions exist [3,11]. In a recent report, Fujiwara etc. [12] provided a study of analyzing the specklegram by speckle pattern division. After dividing the specklegram into several regions, the average of the NIPC of each region was obtained to provide a better dynamic range and a lower linearity error in displacement sensing. Another type of method pay more attention to the variations in the speckle patterns to provide a more powerful analysis when the perturbation applied to fiber is very large. A typical scheme is the morphological processing of the specklegrams [13]. Morphological processing was introduced to obtain the distribution of different bright speckles and new specklegram characteristics were defined, by which the dynamic range of specklegram strain sensors were enhanced.

Different from the above reports, in this paper, fiber specklegrams are treated as different types of textures. An image processing method named gray level co-occurrence matrix (GLCM) is used to analyze the Fourier phase spectra of the fiber specklegrams, which is a statistical way to identify the change of specklegram textures. The statistical features of the GLCMs got from the fiber specklegrams are used to characterize the lateral displacement between the MMF and the launching SMF. In this way, the specklegrams of different MMFs are used to realize the lateral displacement sensing.

This paper is organized as below. Firstly, the image processing method based on the 2D discrete Fourier transform and GLCM is introduced. Then a series of experiments are carried out to confirm the

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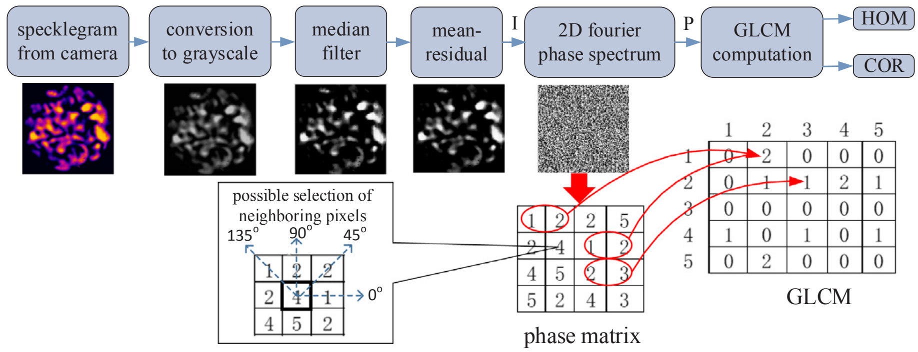

Fig. 1. Flow process diagram for the GLCM analysis of a fiber specklegram.

feasibility of the lateral displacement sensing with the statistical features of GLCM obtained from the MMF specklegrams. By this method, the fiber specklegrams achieved from the MMFs with a wide range of parameters are used to provide a better sensing performance than the conventional NIPC method.

2. Introduction of the image processing method based on 2D discrete Fourier transform and GLCM

The flow process diagram for the GLCM analysis based on the 2D discrete Fourier transform of a fiber specklegram is shown in Fig. 1. After a fiber specklegram is recorded, a circumscribed square region is selected for the further conversion to gray scale, and then the image matrix I is obtained from the median filtering and mean-residual operation. The median filtering can remove salt and pepper noise caused by the camera (such as CCD, infrared camera), and mean-residual operation can remove the average luminance intensity of the image to get a more obvious texture information. Therefore, the preprocessing is helpful for the subsequent processing. Since the phase spectrum of an image contains the position relationship of each frequency component of the image, which preserves the important texture feature of the image and results in the fact that the phase spectra of different images are very different compared with the magnitude spectra [14]. Furthermore, the texture feature extraction of images called Phase-based LBP (Local Binary Pattern operator) has been presented in [15] and [16], which addressed the phase data is more important to human visual perception of texture similarity than the magnitude data. Therefore, a 2D discrete Fourier transform is carried out in order to get the phase spectrum P of a speckle pattern to provide a more clear investigation of the textures in the specklegrams.

To further investigate the difference between the phase spectra of different images, image processing method based on the GLCM is used. The GLCM is a square matrix where both of row number and column number are equal to the number of gray levels in the image, which can reveal certain properties about the spatial distribution of the gray-levels in the image texture. Since the GLCM were proposed by Haralick [17], it has been utilized as the main tool in image texture analysis. It is a statistical method of examining texture that considers the spatial relationship of pixels. The phase spectrum of a MMF specklegram preserves the important texture feature and appears to be a random pattern, thus, it can be treated as a texture image and analyzed by GLCM.

The GLCM is calculated to show how often a pixel with gray-level (or grayscale intensity) value i occurs to adjacent pixels with the value j. Therefore, each element (i, j) of the GLCM represents the number of occurrences of the pair of pixels with pixel values i and j which are at a relative distance d from each other. Mathematically, for a given image phase matrix P of size $M \times N$ with the gray level being G, the elements of a $G \times G$ gray-level co-occurrence matrix M_G with displacement vector $d(d_x, d_y)$ is defined as [18]:

$$M_G(i, j) = \sum_{x=1}^{M}\sum_{y=1}^{N}\begin{cases}1, & if\ P(x, y) = i\ and\ P(x + d_x, y + d_y) = j\\ 0, & otherwise\end{cases}, 1 \le i, j \le G \tag{1}$$

After creating the M_G, several statistical values can be derived from the M_G, two of the parameters named Homogeneity and Correlation are selected to characterize the fiber specklegrams.

(1) Homogeneity, which measures the closeness of the distribution of elements in the GLCM to the GLCM diagonal [19].

$$HOM = \sum_{i}^{G}\sum_{j}^{G} M_G(i, j)/(1 + |i-j|) \tag{2}$$

The diagonal elements of the M_G indicate the group of pixels which have no difference in gray scale value. While calculating the Homogeneity, the weight of element decreases as the distance of elements from diagonal increases. Therefore, in the M_G, the elements near the diagonal have more influence on Homogeneity, which means those pixels with almost no difference affect the Homogeneity greatly. In this way, if a texture has a good local gray scale uniformity, it will get more similar pixels and correspondingly a larger Homogeneity.

(2) Correlation, which provides a similarity of the gray level of the image in row and column direction [20].

$$COR = \left[\sum_{i}^{G}\sum_{j}^{G}((ij)M_G(i, j) - \mu_x\mu_y)\right]/\sigma_x\sigma_y \tag{3}$$

μ_x, μ_y, σ_x and σ_y are the means and standard deviations of rows and columns of the M_G respectively, This statistical feature reveals the local gray correlation in images. If the local elements present a dramatic change, the correlation value will be very small, which indicates that the local area is uneven.

3. Lateral displacement sensing by image processing of specklegrams of step-index MMFs

For a step-index MMF, the number of the supported modes is determined by the normalized frequency V, and V is related to wavelength λ, fiber radius a, the refractive indices of fiber core and cladding n_1 and n_2 as given in Eq.(4)

$$V = \frac{2\pi}{\lambda}a\sqrt{n_1^2 - n_2^2} \tag{4}$$

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