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Evaluation of laser dynamic speckle signals applying granular computing

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ABSTRACT

The laser dynamic speckle phenomenon is a grained and fluctuant interference produced when a laser light is reflected from an illuminated surface undergoing some kind of activity. This phenomenon allows developing practical applications of unlimited use in biology and technology for being a non-destructive process, enabling the detection of not easily observable activities, such as seeds viability, paints drying, bacteria activities, corrosion processes, food decomposition, fruits bruising, etc.

Sequences of intensity images are obtained in order to evaluate the phenomena dynamics, and the signals generated by the intensity changes in each pixel through the sequence are processed with the finality of identifying underlying activity in each point.

This paper offers a new methodology based on granular computing to characterize the signals dynamics within the time domain, reducing the time processing and proposing news evaluation parameters to characterize speckle patterns.

The methodology is applicable to stationary and non-stationary cases, enabling to monitor the phenomenon in almost real time. Two dynamic processes are analyzed to assess the goodness of the proposed methodology: fast paint drying (non-stationary) and corn seed viability (stationary), being obtained results in agreement with the physical behaviour of the observed processes.

1. Introduction

Laser speckle is a high-contrast, random and grained interference pattern produced when laser light is scattered from a diffuse object. Early laser users (e.g. holographers) had to deal with this undesired effect until scientists explained the reason; which was related to a high degree of laser coherence. If the surface is rough compared with the wavelength of the light, rays from different parts of the surface within the area just resolved by the optical system (resolution cell), traverse different optical path lengths reaching the image plane. In the case of an observer looking at a laser-illuminated surface, the resolution cell is the resolution limit of the eye and the image plane is the retina. The resulting intensity at a given point on the image is determined by the coherent addition of the complex amplitudes associated with each of these rays. If the resultant amplitude is zero, a dark "speck" is seen at the point, while if all the rays arrive at the point in phase, a maximum intensity is observed. A more complete description of the phenomenon is provided by Briers [1].

This phenomenon is currently under continuous research in optics due to its remarkable metrological applications [2]. It is called "speckle", and "dynamic speckle" when the surface shows some type of activity

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and the moving particles generate light intensity variations determining images of rough boiling aspect.

Sequences of intensity (gray scale) images captured in fixed time steps are obtained to scan the phenomenon. The noisy resulting images capture the intensity of the specks and do not permit clearly to distinguish the illuminated object or surface. The intensity variation of each pixel through the sequence determines a one-dimensional signal denominated "time history speckle pattern" (THSP) [3]. These signals show a highly random behaviour; hence the sample characterization involves the discovery of hidden patterns in a noisy frame. Braga et al. [4] showed that THSP did not behave as white noise, providing evidence that these signals contain reliable information of the dynamic belonging to the sample.

Different approaches have been introduced to analyze THSP in order to evaluate the behaviour of the illuminated sample, among them: first- and second-order statistics of speckle fluctuations [1], estimates using the full-width at half-maximum of the autocorrelation function [5–8], wavelet tools [9–12], clustering and clipping methods, as well as other tools oriented towards signals periodicity detection and description are being employed to gain information about the underlying dynamics [13–15].

Experimental factors state which speckle tracking algorithm is best suited for a given situation. There is not a single precise method applicable to every type of stationary and non-stationary experiment neither there is knowledge of the causes that conditioned the signal behaviour. The computational procedures require a large amount of images, sometimes requiring pre-processing and needing to be processed at regular intervals, that is to say, they cannot be processed in real time. The speckle signal processing is a topic currently under study.

Different methodologies are currently applied to several speckle experiments trying to take out benefit of the phenomenon, for example: coatings drying [16], biological observations [17,18], fruits bruising [7,19], bio-medical applications [1], and evolution in porous media [20], among others.

Concepts already put forward by Zadeh, such as fuzzy sets [21] and granular computing [22], are proposed in this paper as a novel methodology for THSP processing, using a fast and natural way. The methodology considers the uncertainties characteristic of the phenomenon, facilitating the identification of the significant changes of the signals.

Fuzzy and granular computing concepts are employed in signal processing with different objectives such as filtering, feature extraction, and signal classification [23–26]. This work proposes to evaluate the signal dynamic in a direct way, obtaining an "activity index" to characterize THSP signal.

The work is organized in the following way: Section 2 defines a framework based in fuzzy sets applied to gray intensity values to determine information granules. Section 3 explains the methodology employed to characterize the dynamics starting from the granulated signal. In Section 4, two experiments are presented, a stationary and a non-stationary, to show the methodology application. In Section 5, the results obtained in both experiments are presented. One of them is compared with results obtained by other methods. Finally in Section 6, the advantages obtained with the methodology employed are presented.

2. Framework

The objective proposed herein is to measure the activity in spite of the physical factors affecting the speckle image. This is an abstraction process that attempts to determine the behaviour of single specks or particles, considered equivalent to a pixel, through a sequence of images.

Gray pixel arrays (GPA) in which each array element represents the pixel value in an instance of image sequence are used. Each GPA represents a signal in the time domain.

Granular computing deals with information representation in the form of a number of entities or information granules. Information granules are made up of a collection of entities, usually arising at the numeric level, arranged together due to their similarity, functional adjacency, indistinguishability, coherence or alikeness [22]. Details of this paradigm have been compiled by Pedrycz [27].

The information granules contribute to condensing a signal and represent it as a set of temporal granules through an abstraction mechanism that synthesizes the information. This representation preserves the granules identity in spite of some small fluctuations occurring within the experimental data.

The methodology presented in this work intends to granulate the signals in function of similar intensities values. The relative quantity of granules, or granules density in each GPA, will specify the activity in each pixel of the registered images sequence. The principal difficulty presented deals with the way to determine similarity in a random and uncertain behaviour.

The fuzzy sets theory, developed in other reported works [21,28,29], is adequate for this purpose, since it enables to make reference to vague and overlapped concepts. The membership of an element to a fuzzy set is defined by a function that takes gradual values in the real interval [0,1] and usually different membership functions can be overlapped partially. For example, the dark, medium and light concepts can define fuzzy sets in the values range of gray levels; they are subjective terms without clear limits, that is to be said that they can be partially overlapped. This concepts are proposed to characterize pixel intensity and in this way to granulate each GPA in function of the similarity of their values.

The following three components are employed to define fuzzy granularity (Gr): the information to be processed (X), the formal framework of information granules (F) and the frame of reference (A):

$$\mathrm{Gr} = \langle X, F, A \rangle \tag{1}$$

For the case under study, X is a GPA. F is obtained applying fuzzy sets membership functions to X, and A is the set of fuzzy terms corresponding to gray level values, defined as $A = \{\text{dark, medium, light}\}$. Each granule is then represented by the dark, medium or light fuzzy property.