Fuzzy Granular computing and Dynamic Speckle Interferometry for the identification of different thickness of wet coatings

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Abstract— Granular computing and fuzzy sets concepts are proposed here as a novel method to process speckle images stacks in a fast and natural way. Speckle images are the result of scanning a phenomenon that occurs when a beam of coherent light illuminates a sample in which there is any type of activity, not visible, which produces a pattern variable in time. This process has been applied to the drying of paints without contact. The proposed methodology evaluates the intensity variations, considering the uncertainties proper of the phenomenon, being necessary only few images to characterize the activity. In many manufacturing processes it is of great importance the automation of the thickness evaluation in fresh film coatings. Examples about drying of paint process and activity images in paint layers are presented. The results obtained show that this methodology requires less information and computational efforts than the usual methods and also allows almost real time processing. This granular computing approach should be of interest in automatic processes, adding quality test spots of fresh films to improve the performance of the painting tasks.

Keywords: Dynamic speckle interferometry, paint drying, granular computing, fuzzy sets.

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1. Introduction

The monitoring and control of the thickness of wet coatings in a manufacturing process is often a critical task. Thickness measurement devices that are based on contact like ultrasonic testing, eddy-current testing and electromagnetic testing, are not suitable for films of wet coatings. Several methods based in non-contact procedures are not practical like coherence tomography [12] which is not advisable for opaque coatings, the thermal-wave diffraction tomographic microscopy [13] that needs a high time consuming process to construct cross -section image of the object and the terahertz tomography [23] that needs a complex optic set-up.

The application of Dynamic Speckle Interferometry (DSI) to the drying of paints was reported earlier [1], [3],[11], and also a practical development has been presented as an Adaptive Speckle Imaging for monitoring the formation process of film on an regular surface topography [6]. Nevertheless coating processes are often carried on in irregular surfaces, and the evaluation of an inhomogeneous drying pattern must be done considering a full field image. Many algorithms oriented to process a complete field image, based in statistical and classical signal processing operations have been also reported [5], [2], [18]. In this paper we propose a method that discovers different thickness zones according with their drying times based in fuzzy granular computing. This method has also been successfully applied to a viability test of corn seed [8].

The paper is organized as follows: in the Dynamic Speckle Interferometry, Section 2 , the principles and main features of the image acquisition technique are given. The basis of the Granular Computing with Fuzzy Sets (GCFS) applied to one-dimensional variables is approached in Section 3. The Speckle Signal Processing, Section 4, explicates the particular methodology applied to the time series belonging to the evolution of each image pixel.

In Section 5, the proposed methodology was evaluated with two different experiments, in the first one the estimation of the drying time of a latex coating is approached while the second deals with the identification of equal thickness regions of wet coating on an irregular surface.

The performance of the GCFS is tested against the Inertia Moment descriptor [1], the GCFS method showed a better performance as well as low computational cost, using an algorithm feasible of hardware implementation.

2. Dynamic Speckle Interferometry (DSI)

When a coherent light source (laser) illuminates a non-polished surface, surface roughness causes random interference phenomena, known as “speckles”. The phenomenon is originated by the different path lengths between the surface different scattering points and an observation source. Optical systems can be used for obtaining a scan of the phenomenon and register it in successive images. The images show peculiar speckle patterns depending on surface roughness, on the incoming light wavelength and on the numerical aperture of the imaging optical system. See Fig. 1.

When the illuminated surface presents some activity type the speckle pattern varies. During a slow movement the speckles may be preserved and be recognized in the successive images, but in the presence of higher activity the speckles intensity varies randomly with a rough boiling aspect. This is a very complex phenomenon that could be used to characterize particular and interesting dynamics. The activity variations permit the assessment of diverse phenomena, such as microorganism motility [22], seeds viability [4], fruits bruising [16], and particularly the drying of coatings [1], [3], [11] some of them with considerable economic or biological interest.

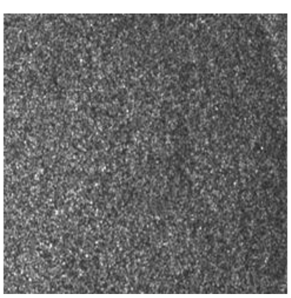

Fig. 1. Raw Speckle image

Activity is, in many cases, due to several physical reasons. The details are mostly unknown but an estimation of overall activity is sometimes useful. So, several mathematical methodologies have been developed in order to obtain different dynamic speckle descriptors and to develop practical applications of the phenomenon [17], [15], [21].

3. Granular Computing – Fuzzy Sets

Granular computing deals with representing information in the form of a number of entities or information granules. Information granules are viewed as linked collections of objects (data points, in particular) drawn together by the criteria of indistinguishability, similarity or functionality [19].

Information granules and the ensuing process of information granulation are vehicles of abstraction leading to the emergence of high-level concepts [25].

The fuzzy set approach offers interesting and useful features supporting processes of information granulation and the information granules resulting therein.

Fuzzy sets support modelling of concepts that exhibit continuous boundaries. The overlap between fuzzy sets (that is an inherent phenomenon occurring in the theory of fuzzy sets) helps to avoid a brittleness effect manifesting when moving from one concept to another. This becomes particularly crucial in the case of using data that could be affected by some noise. Fuzzy sets exhibit a well-defined semantics and emerge as fully meaningful conceptual entity building modules identified in problem solving [24].

In the image speckle case, the speckle intensity transformation in time can be seen as temporal granulation [20], where *dark*, *light* and *medium* granules are merged. The *dark*, *light* and *medium* concepts are overlapped and its limits undefined, although the intensity values are clearly defined. They are an abstraction in the human reasoning task.

Considering the classical set theory, given a set of objects X, whose elements are denoted x_i, and a classical subset A of X, the membership of each x_i to A is viewed as a characteristic function $\mu_A(x_i)$ from X to $\{0,1\}$ such that:

$$\mu_A\left(x_i\right)\begin{cases}1\,iff\ x_i\in A\\0\,otherwise\end{cases}\tag{1}$$

If the μ_A is allowed to be the real interval [0, 1], A is called a fuzzy set and μ_A is the grade of membership of x_i in A. A is a subset of X that has no sharp boundary (see Fig. 2).

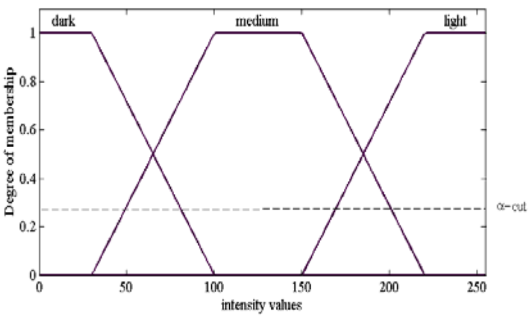

Fig. 2. Fuzzy sets and membership functions

A is then characterized by the set of pairs [10]:

$$A=\{(x, \mu_A(x_i)), x_i \in X \text{ and } \mu_A \in [0,1]\} \qquad (2)$$

The support of a fuzzy set A is the ordinary subset of X:

$$Supp\ A=\{x_i \in X, \mu_A(x_i)>0\} \qquad (3)$$

The set α-*cut* of a fuzzy set A is defined as:

$$A_\alpha=\{x_i \in X,\ \mu_A(x_i) \geq \alpha\},$$
$$\mu_{A_\alpha}(x_i)\begin{cases} 1\ iff\ x_i \in A_\alpha \\ \mu_A(x_i)\ otherwise \end{cases} \qquad (4)$$

4. Speckle Signal Processing

As the aim of this work is the identification of Region of Interest in a stack of speckle images, a pixel to pixel activity analysis must be performed.

The activity of a single pixel in the sequence of images is estimated by the density of information granules contained in the sequence. Each granule of information is defined using intensity fuzzy concepts as *dark, medium* and *light*. Hence, fuzzy membership functions must be defined for the discernment of the granules in term of their properties. Trapezoidal fuzzy membership functions were selected in this work; and their parameters were defined with the help of the histogram of the gray levels in one image. The parameters of each fuzzy set were selected in a way to balance the quantity of pixels belonging to each set, allowing independence of the sample illumination level.

The three fuzzy concepts are applied to intensity values of a pixel, through the speckle pattern sequence (X). By eq. (2), A_{dark}, A_{medium} and A_{light} sets of (x_i, $\mu_{Ak}(x_i)$) elements, with k={ *dark, medium* and *light*} are obtained.

Each granule in the X signal is defined as a sequence of contiguous elements belonging to a same fuzzy set. The quantity of granules belonging to X, related to T samples (images) is computed as:

$$Q_T=\sum_k \left| seq_{i,k}\left(\mu_{A_{k\alpha}}(x_i)\right)\right| / T \quad i=2,\ldots,T \qquad (5)$$

where $seq_{i,k}(cond)$ represents continuous sequence of values in which *cond* condition is true. Detail of the behavior applied to some signals can be shown in Fig.3 [7].

The overlapping of the fuzzy concepts will influence in the hardness and quantity of the granules. The selections of fuzzy sets parameters by means of the intensity histogram facilitate an adequate determination. The α-*cut* is assumed 0, but different α-*cut* in [0,1] could be applied to reduce the overlapping (eq. 4).

The estimation in almost real time can be obtained considering the previously accumulated number of granules. This methodology permits the identification of variations, reducing the sensitivity to small interferences making the methodology more robust.

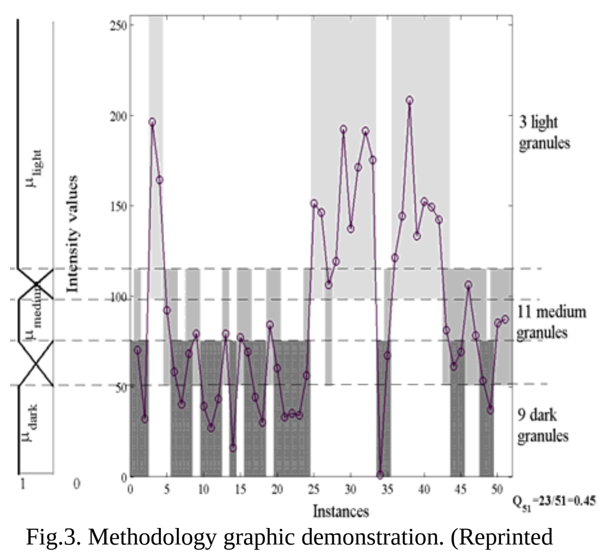

Fig.3. Methodology graphic demonstration. (Reprinted from Signal Processing, A.L .Dai Pra, et al., Evaluation of laser dynamic speckle signals applying granular computing, Signal Process 89 266–274,Copyright (2009), with permission from Elsevier.)

5. Experiments

To test the application of the proposed methodology two experiments were performed. The first aims to assess the drying time of a paint coating spread on a flat tray and the second evaluates the potential of discovering differences in the thickness of a wet coating over an irregular surface.

5.1 Drying of latex paint.

In the drying of latex paint, the dynamic speckle phenomenon seems to be a non-contact useful tool [1] for assessing the time evolution of painted surfaces. Its sensitivity to scattering centers movement and refractive index changes helps to determine the different stages. This study case can be followed through gravimetrical measurements permitting evaluate the goodness of the results obtained through of the new technique.
A low power attenuated He-Ne laser (5mW, λ-633 nm) was used to illuminate the samples. The signal was collected by a CCD lens less camera (free propagation). Care was taken to keep the laser intensity constant during data acquisition. Speckle size was adjusted so that they were well resolved by the CCD pixels. The experiments were made with slow drying paint samples prepared by spreading the paint on a glass substrate by means of an extender.
The images were captured in 0.08s time steps and a Time History of the Speckle Pattern (THSP) image was built with 512 successive instantiations. A THSP is a convenient way to show the time evolution of a speckle pattern, when the phenomenon is stationary. Only the pixels of a column (usually the center one) are selected in each speckle pattern and a composed image is built by stacking side by side these columns [14]. This image shows variations according time elapses. This THSP stands for what is assumed to be a representative sample of its current drying state.
Twenty-three THSP (512 x 512 pixels) patterns were registered. The time interval between two consecutive THSP drying stages was 4 min.

5.2 Thickness of coating

As the previous experiment gave successful results for detecting different stages in paint drying process and it is accepted that different thickness of wet coating are correlated with different stages of the drying process, the ability to discover a hidden topography under a wet coating film was evaluated with another test.
This test was performed by spreading a thin layer of fresh paint on an object with a known irregular surface; an argentine coin was used for this purpose. Regions where the paint layer was thinner were expected to be drier than those where the layer was thicker and consequently less active.

6. Results

6.1 The drying of latex paint

Figure 4 shows three of the 512 registered THSPs as described in the section II. The first, with highest activity, represents fresh paint; the second, a middle stage, with the paint beginning to dry and the third corresponds to dry paint. It is possible to visualize the changes of granularity in the different stages. Active samples show fast intensity changes while inactive ones give rise to elongated shapes in the time direction.

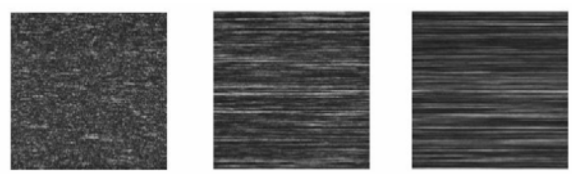

Fig. 4. Three stages of Latex paint drying THSP

For each THSP, the account of granules considering 512 samples (Q_{512}) was applied to each row (Eq. 5), the 512 results were averaged and a unique value was obtained for each. Fig. 5 is a normalized graphic of the Q_{512} obtained for THSP recorded at different times is compared with those obtained with gravimetric measurements (GM) and also with the Inertia Moment (IM). The last descriptor was calculated using a particular second-order moment called the inertia moment (IM) of the modified co-occurrence THSP matrix (MCOM) [1]. This measurement is similar to one currently used in photon correlation spectroscopy called photon structure function [7]. Comparing both descriptors with the GM values, the GCFS shows a better approximation during the first third of the drying time lapse, decreases monotonously as the paint dries showing a similar behavior as the gravimetric curve. The computational cost of the GCFS has showed at least three times less than the IM.

To test the process sensitivity to the amount of required information, the same calculation was repeated to THSP built with different image sizes. Figure 6 shows the result of applying Eq. (5) to THSPs of: 512x512 pixels, 200x200 pixels and 100x100 pixels. It can be observed that the Q_T obtained with different sizes of the THSP window shows no significant difference; hence the proposed method could be implemented with a lower window size performing similar results.

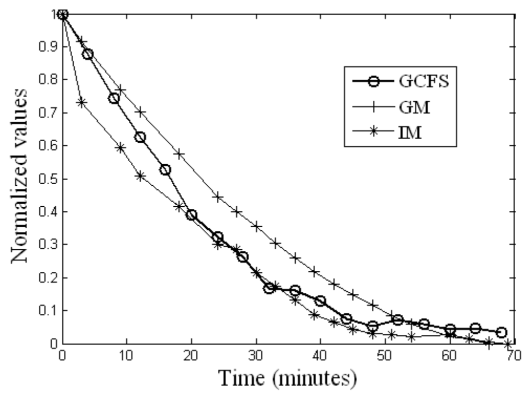

Fig. 5. Fuzzy granular index activity (GCFS) vs. Gravimetric measurement (GM) and Inertia Moment (IM)

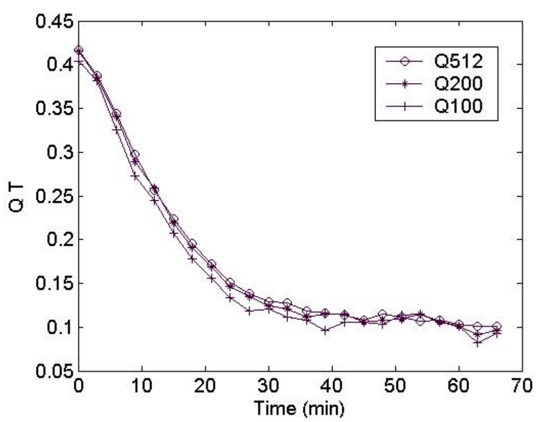

Fig. 6. Latex paint drying results for different window sizes

6.2 Thickness of coating

To segment regions of similar activity in an extensive sample, the speckled images must not be obtained by free propagation (as in the previous experiment) but consisted in subjective speckle focused images formed by an objective (usually f=50mm, f/# = 16), as shown in Fig. 7. This is the case where different regions of the objects differ in their activity. An expanded laser beam is used for the illumination and the CCD camera registers the image with Fraunhofer subjective speckle. In this case a set of sequential images have to be registered and processed. Then, a new image of the sample can be assembled using the calculated Q_T with Eq (5) corresponding to each pixel time evolution. Hence dark regions identify low Q_T level and the bright ones are the regions with higher Q_T.

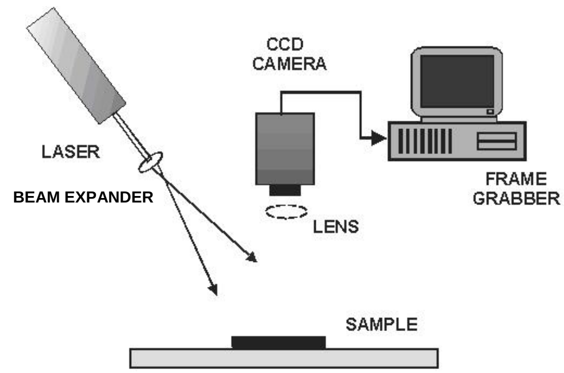

Fig. 7. Experimental set up: The lens in broken lines and the beam expander are included only for the coin image experiment.

Complete images of the speckle pattern of the painted surface were processed. The layer of paint on a surface of known topography (a coin) was uniform. No hint of the surface details could be observed in each speckle pattern before processing Fig.1. The results of the processing of each pixel considered as a time series are shown in Fig.8. Activity reproduces the relative thickness of the paint layer and hence of the underlying not visible topography. As no spatial window averaging is required there is no tiling effect in the result. Notice that the resulting image is of good quality, it shows no speckle traces and small details of the coin are very well resolved. The rim of small spheres can be clearly distinguished.

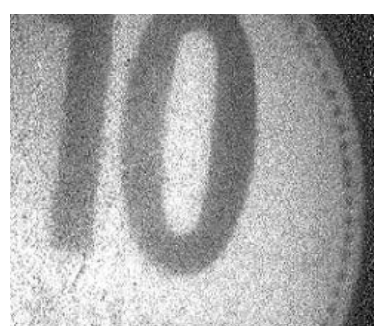

Fig. 8 Activity image as the result of a fuzzy granular process, showing Argentine 10 cents coin topography.

Figure 9 shows a sequence of activity images. The number under each subimage indicates the quantity of former frames evaluated. Starting from the resulting 10th pattern, where the coin is already distinguisible, only some results are shown to avoid repetitive images. It can be observed that the activity image progressively improves.

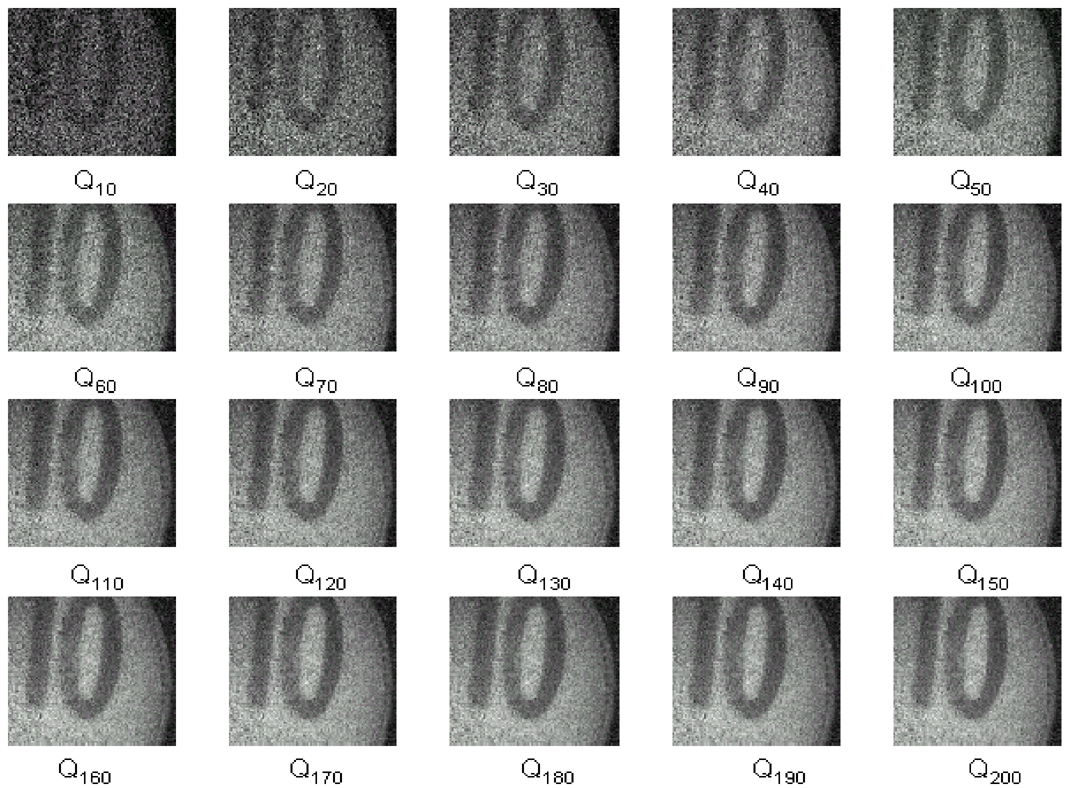

Fig. 9. Progressive sequence of activity images started from the first speckle pattern. The number under each sub-image indicates the quantity of processed frames.

7. Conclusions

The use of fuzzy granular computing to identify different thickness in wet coatings was analyzed. The results showed that the speckle signal processing with fuzzy granular computing was capable to segment images according to zones of different thickness.

The processing involves low computational cost and it can be used with smaller amount of data than other methods. This feature makes it viable to be hardware implemented using Field Programmable Gate Arrays [9].

The analysis of drying time of specific film coatings in conjunction with the study of relative thickness is foreseen in future studies to obtain an estimation of the fresh film thickness. The addition of such feature would be of interest in a manufacture process, adding quality test spots of fresh films to improve the performance of the painting tasks.

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