A Methodology for Laser Speckle Simulation in Controlled Dynamic Processes

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Abstract - The use of coherent light in imaging is the basis of several technologies that extends from nanotechnology, biomedicine, structural biology to metrology. Regarding laser speckle imaging in health-related conditions, in recent years several applications have been developed, emphasizing the potential of laser speckle as a functional imaging methodology, either used as individual methodology or in a multimodal imaging scheme. To assess distinct acquisition methodologies, several experimental protocols have been tested, but also new activity descriptors have been developed. These image processing derived descriptors are core to the speckle characterization in dynamic physiological conditions. Accordingly, the use of computer simulation algorithms to obtain the phenomena, avoiding acquisition noise is a research topic with great interest among the community, as a way to test the descriptors performance in a controlled way. In this work, a methodology for laser speckle simulation of dynamic processes is presented. The proposed algorithm allows controlling the way the process varies by setting a linear, quadratic, sinusoidal or mixt behaviors, during the simulation period.

Keywords – Computer simulation, Laser Speckle, Computer Vision, Signal Processing

I. INTRODUCTION

Speckle is an optical interference phenomenon obtained when a coherent source of light is projected into a rough surface. The scattering surface can either be static or have micromovements due to some dynamic process (occurring in it or underneath the surface itself) able to modify its texture along time. Although the physical principles have been firstly described by Newton, the advances in camera technology and sensors (CCD sensors), as well as in laser technology, emerged as an impulse to look at the speckle interferometry in a different perspective. Instead of a noisy phenomenon to be avoided, laser speckle became an information source to be studied, as it carries information about the dynamics of the scattering surface. In research areas related with synthetic aperture radars [1], biomedical imaging ultrasounds [2] and optical coherence imaging [3], speckle interference of the reflected wavefronts is filtered to improve the accuracy of the obtained information. Also in industrial applications, laser speckle have been used to measure deformation, shape, and roughness of materials (Speckle metrology).

More recently, with the advances in optical sensors, major attention has been devoted to the reflected wavefronts as a vehicle of information about the dynamics occurring in the sample surface. Of particular biomedical interest are perfusion studies related to cortical ischemia [4], blood flow speed [5] and the assessment of burn recovery [6], among other biomedical studies.

Given the type of information that is captured by the camera sensors and its inherent complexity and variability in statistical terms, several descriptors have been proposed to establish quantitative measures regarding the speckle variation pattern [7–9]. The way to assess the accuracy of such measures is mostly done by performing experimental tests, where stimulus-response protocols are followed as a way of assessing sensitivity/specificity regarding the predefined stimulus.

The validation of activity descriptors based on experimental procedures can be replaced/complemented by computational simulation. This procedure has gained some relevance in speckle imaging in the last years, contributing to a clear insight into the physical phenomena under study. Computer simulation of speckle has the advantage of generating the phenomenon avoiding the errors and noise associated with the experimental process. The test of new descriptors based on simulated signals is also a way of avoiding previous processing (e.g. filtering) in the experimental signals. In the majority of the acquisition systems it is difficult to fully characterize a priori the type of associated noise, thus simulation algorithms are seen as a very useful tool in speckle imaging research.

In this work, an algorithm for speckle simulation will be presented to enable computer simulation of syntetic speckles in controlled dynamic processes. The algorithm is based on the Copula simulation model proposed by Duncan and Kirkpatrick [10] and will be tested by using classical activity descriptors with and without added noise. The simulation algorithm will be tested in controlled dynamics processes with linear, quadratic, sinusoidal and mixt sinusoidal variation profiles.

In the following of this work, in section II the simulation algorithm will be presented, and in section III the results will be shown and discussed. The last section is dedicated to conclusions and future work.

II. SIMULATION ALGORITHM

A. Mathematical background of the Copula

Methodologies for computer simulation of speckles often use Fast Fourier Transform (FFT) of a phase matrix
By using solely this approach the output of each simulated speckle are independent of each other. In [10], Duncan and Kirkpatrick proposed a methodology based on a temporal correlation function, which is summarized in this section.

The Copula algorithm is based on the Sklar’s Theorem, in which a two-dimensional distribution function \( H \) and two marginal distribution functions \( F \) and \( G \) are related by the existence of copula \( C \), as in (1)

\[
H(x, y) = C(F(x), G(y)).
\]

Let \( X_1 \) and \( X_2 \) be two uniformly distributed, statistically independent, random variables (RV). By applying the Box-Mueller transformation to each of these two variables, two new variables are obtained (as shown in (2)) representing polar coordinates of the points from \( X_1 \) and \( X_2 \),

\[
Y_1 = \mu + \sigma \sqrt{-2 \ln(X_1)} \cos(2 \pi X_2),
\]

\[
Y_2 = \mu + \sigma \sqrt{-2 \ln(X_1)} \sin(2 \pi X_2),
\]

where in (2) \( \mu \) is the mean and \( \sigma \) is the standard variation. The obtained joint density distribution of the bivariate function \((Y_1, Y_2)\) is a Gaussian with mean and standard deviation \( \mu \) and \( \sigma \) respectively. This method produces a pair of random variables having an arbitrary correlation coefficient that will be used in the proposed methodology to relate the sequence of simulated speckle frames.

B. Computer Simulation Algorithm

According to the method proposed in [10] to create the simulated speckle, a circle of radius \( D/2 \) filled with complex numbers with phases uniformly distributed in the interval \([0, 2\pi]\) is created inside a square having \( L \times L \) dimensions. The exponential probability distribution of the speckle pattern will be obtained after the multiplication of the 2DFFT of the square by its complex conjugate.

At the proposed methodology, to obtain the phase angle a multiplicative height \( m \) is introduced as defined in (3), where \( T_{ij}, j = 1, 2 \) is obtained by a percentile transformation from \( Y_{ij}, j = 1, 2 \) in (2), and \( i \) is the frame index in the simulation.

\[
\phi_{x,1} = 2 \pi m_{1} T_{1}; \quad \phi_{y,2} = 2 \pi m_{1} T_{2}
\]

The algorithm proposed by Duncan and Kirkpatrick in [10] was built to produce continuous phase trajectories between the two bounds of the correlation interval (e.g. \(-1 < r < 1\)). The multiplicative factor proposed at the present work to be included in the process of obtaining the phase, will maintain the above characteristics but also introduces a varying controlled weight factor. This will maintain the correlation dependence between frames associated to a given trend.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Image processing of speckle frames allows obtaining qualitative and quantitative measures of the dynamics of the process under study. Classical measures include contrast, some of its derivative measures (e.g. perfusion, velocity, ... ) and Time History Speckle Pattern (THSP) among others. Contrast, as defined in (4) is the Coefficient of Variation of the intensities in each frame, where \( \sigma \) is the standard deviation and \( f \) the mean.

\[
K = \frac{\sigma_f}{f}.
\]

In this work, the contrast will be used as a measure to test the results of the proposed algorithm. In order to calculate the contrast, a kernel matrix is applied, whose dimension must be suitable to the speckle graining size. The simulated speckle size depends on the relation between \( L \) and \( D \) (dimension of the square and diameter of the circle) previously defined. The quotient between kernel size and speckle size, as defined in (5), will be used to study the minimum kernel size to be used in the simulations in order to avoid oversampling.

\[
\rho = \frac{\text{Kernel size}}{\text{Speckle size}}.
\]

A. Definition of parameters for the simulation

Previous studies have shown that the minimum speckle size to avoid undersampling is the double of the pixel size [11]. Likewise, the kernel size needs to be adapted to avoid undersampling issues in the spatial averaging when calculating the contrast.

In order to test the contrast variation with the ratio \( \rho \) defined in (4), a set of simulation studies were conducted whose results can be found in Fig. 1. A sequence of simulated static speckle was created using the above described method considering \( m(l) = 1, \; l = 1, 2, \ldots, N \) where \( N \) is the number of simulated frames (in this particular case, the simulation is the same as proposed in [10]). Additionally, by using the obtained simulations, Gaussian noise was added to test the effect of noise in the imposed predefined trend. The range for the level of added SNR was defined to include the minimum level of 5, according to the rose criterion.

![Contrast variation as a function of the ratio ρ.](image-url)

According to the results in Fig. 1, contrast values present an initial increasing pattern tending to stabilize as \( ρ \)
increases. This pattern is the same for the cases where the noise was added, in which an overall inverse relation is seen between SNR and contrast values.

The dashed vertical line in Fig. 1 indicates the $\rho$ value for the minimum speckle size (i.e. 2) and kernel size 7.

B. Dynamic simulations

The main objective of this work is to present a methodology to simulate speckles obtained from dynamic processes, in which the activity trend is previously known. To test the ability of the algorithm to reproduce the predefined trend, 5 mathematical models for the activity variation were simulated. In Fig. 2 the five models are presented in the left column: linear monotonic (A), parabolic (B), sinusoidal (C), sinusoidal crescent (D), mixt monotonic sinusoidal (E). The corresponding contrast obtained with the simulation studies is presented in the right column. In the simulations a speckle size of $4 \left( \frac{L}{D} = \frac{256}{64} \right)$ was applied jointly with a kernel of dimension $9$ for the contrast calculations.

![Figure 2](image-url) Figure 2. Nature of the dynamic process (at the left) and contrast after simulation (right column).

As is possible to observe by comparing the left and right graphs in Fig. 2, the contrast for each frame follows the trend pattern created in the simulation. Although this is a qualitative assessment, and no relation between the $m(i)$ values and contrast were exploited, the proposed approach can be used to validate new dynamic descriptors.

The influence of the added noise in the simulation was also studied, by joining in the monotonic linear case three noise levels ($SNR = 10, SNR = 5$ and $SNR = 2$). The results are presented in Fig. 3.

From the results in Fig. 3 it is possible to observe slight variations in the contrast curve, however, the global pattern and contrast values do not seem to be influenced by the noise level (compared with the noiseless contrast graph, the first graph in Fig. 3, $A_s$). In fact, the contrast calculation is itself a form of filtering (a spatial low pass filter) thus the noise does not influence the contrast profile.

IV. CONCLUSION

In this work, a method to simulate dynamic speckle from a process in which the dynamic behavior (e.g. activity) is known was presented. The algorithm is derived from the Copula methodology, and adapted to encompasses controlled correlation between frames.

To test the proposed algorithm, 5 mathematical models for the activity were tested. Moreover, one model was also tested against 3 SNR noise levels. The results point to an algorithm that can be used to simulate dynamic speckle patterns which are also robust against noise.

![Figure 3](image-url) Figure 3. Contrast after simulation with linear pattern and for three levels of noise.
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