Texture analysis using complex system models: fractal dimension, swarm systems and non-linear diffusion

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Abstract—**Texture is one of the primary visual attributes used to describe patterns found in nature. Several texture analysis methods have been used as powerful tools for real applications involving computer vision. However, existing methods do not successfully discriminate the complexity of texture patterns. Such methods disregard the possibility of describing image structures by fractal dimension. Fractality-based measures allow a non-integer geometric interpretation with applications in areas such as mathematics, physics, and biology. The central hypothesis of this work is that textures can be described as irregular fractal surfaces due to their complex geometry. Pushing the limits of the state-of-the-art, the results achieved in the four methodologies described in this work demonstrated the potential of using texture features in tasks of pattern recognition. The contributions of this work shall support significant advances in materials engineering, computer vision, and agriculture.**

Keywords-**texture analysis; fractal dimension; swarm system; non-linear diffusion; complex networks**

I. INTRODUCTION

[1]Texture is an important visual attribute in computer vision with many areas of applications. Recently, texture analysis has been widely applied to remote sensing [1], [2], industrial inspection [3], [4], medical image analysis [5], [6], face recognition [7], [8], among many others. Although the human visual system can easily discriminate textural patterns, the description by automatic methods has been a great challenge. Indeed, there is no universally accepted definition of texture. It is usually referred to as a repetitive pattern that can vary according to the size, which produces different tactile sensations associated with roughness, coarseness, and regularity. Furthermore, texture patterns are related to the physical properties of surfaces present in images, making them a powerful tool for image analysis.

Texture analysis has been an active research field in the last decade. The proposed methods have been grouped according to the mathematical aspects used to handle the patterns present in the images. There are five major categories: structural, statistical, spectral, model-based, and agent-based. The structural methods rely on primitives that provide a symbolic description of the images [9]. The idea comes from concepts on mathematical morphology, which describes an image by evolving morphological operations with different sizes of structuring elements [10], a useful technique to handle shapes in textures.

Statistical methods represent textures by the spatial distribution of the gray-level pixels in the image. One of the best methods of this category, and still very popular, is *co-occurrence matrices* [11], [12]. In the same line, Dmitry Chetverikov [13] introduced the technique named *interaction map*. Similarly, Ojala et. al. [14] proposed a method that describes images based on the occurrence of gray values on circular local neighborhoods; it is named local binary patterns (LBP). Xiaoyang et al. [15] extended the idea of LBP to local ternary pattern (LTP), which considers the magnitude of pixel derivatives along with its sign to generate the ternary code. In the work of Hadid et al. [16], the authors present a comparative study using 13 variants of local binary patterns for gender classification.

Model-based methods were proposed with the assumption that textures can be represented by mathematical models, including stochastic models of Markov random fields [17], [18] and fractality [19]. Particularly, fractal geometry has drawn great attention on the task of describing textures [20]. The main reason is because fractal geometry is able to describe irregular or fragmented shapes of natural phenomena, as well as other complex objects that traditional Euclidean geometry is not able to describe. The fractal concept is expressed by the time-domain statistical scaling laws and is characterized by the power-law behavior of physical systems. This idea makes use of the geometrical interpretation of objects and takes into account the degree of regularity of the structure related to its physical behavior [21]. Recently, Goncalves et al. [22] proposed a hybrid fractal-swarm method for texture analysis.

Most of the methods used in texture analysis are restricted to the analysis of the spatial relations over small neighborhoods, or they are based on the extraction of global features of the whole image on a single scale. As a consequence, they do not perform well in high-complex geometry textures. In contrast, spectral methods or signal processing methods, including Fourier analysis [23], Gabor filters [24], [25], wavelet transform methods [26], [27], were developed inspired by evidence that the human visual system describes images by

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[1]This manuscript is related to a Ph.D. thesis. The thesis can be downloaded at http://www.teses.usp.br, by clicking on the option Advanced Search; select Doctoral Thesis, and then type the first two names of the main author.

the frequency domain. However, the Fourier transform lacks spatial information, what impairs its potential for image description. Although Gabor filters present joint image resolution in both the spatial and frequency domains, they do not describe well coarse textures; this is because the energy of such textures is concentrated in subimages of lowest frequencies [28]. In contrast with Gabor filters, wavelets decompose a texture image into a set of frequency channels. However, wavelet analysis is basically a linear analysis and suffers from uniformly-poor resolutions over different scales and from its non-data adaptive nature, since the same wavelet basis is used to analyze all the data [29].

II. Goals and Contributions

The goal of this work is to propose solutions to overcome the drawbacks of current texture analysis methods, as observed in the literature. To reach this goal, we have proposed new methods for texture description based on complex systems, including fractal dimension, swarm systems, non-linear diffusion models, and complex networks. We have addressed two main issues found in typical statistical and model-based texture descriptors: (1) the lack of a multiscale representation to capture the richness of local features in different levels of observation; and, (2) although fractal descriptors proved to be a promising texture descriptor, current methods do not explicitly consider the neighborhood relation in terms of the gray levels of the texture. In this work, we evaluated our methods over four texture benchmarks: Brodatz [30], Vistex [31], Outex [32] and Usptex [33]. In addition, our methods were compared with state-of-the-art texture methods. The motivation to develop our methods is that they are suitable for real-world applications, as in material engineering and agriculture, leading to better or automatic decisions. As we show along the text, we focus on nanomaterial quality assessment and on plant disease identification in soybean leaves.

The first contribution of this work is a methodology for texture description. We carefully investigate all the steps of a swarm system method named *artificial crawler*, proposed first by [34], [35]. The original method was proposed to have the iterative crawling step moving only in the direction of maximum pixel intensity, thus characterizing regions of high intensities in the image. However, in texture analysis, regions of low intensities are as important as regions of high intensities. For this reason, we proposed a new rule of movement that also moves the agents in the direction of lower intensity. We developed an improved method for assessing the quality of the silk fibroin scaffolds [36] with two rules of movement: maxima and minima. Our goal is to provide an effective method to support visual analysis, thus reducing the subjectivity of the human analysis. We evaluated the potential of the silk fibroin by including glycerol in the solution during scaffold formation. This work was published in the *Computational Science and Discovery Journal* [37].

The second contribution of this work is an extended methodology based on the energy information of the artificial crawler swarm system extracted from two rules of movement. Similar to the method proposed in the first contribution, each agent is able to move to the higher intensities, as well as to lower ones. Although we can find the minima and maxima of images directly, the underlying idea is to characterize the path of movement during the evolution process. Our method differs from the original artificial crawlers since we quantify the state of the swarm system after stabilization by employing the Bouligand-Minkowski fractal dimension method [20]. In the method, the energy information was considered the most important attribute due to its capacity of representing the interaction between the movement of agents and the environment. This work was published in the journal *Physica A: Statistical Mechanics and its Applications* [22] and, an example of the path configuration for 1,000 artificial crawlers is presented in Figure 1.
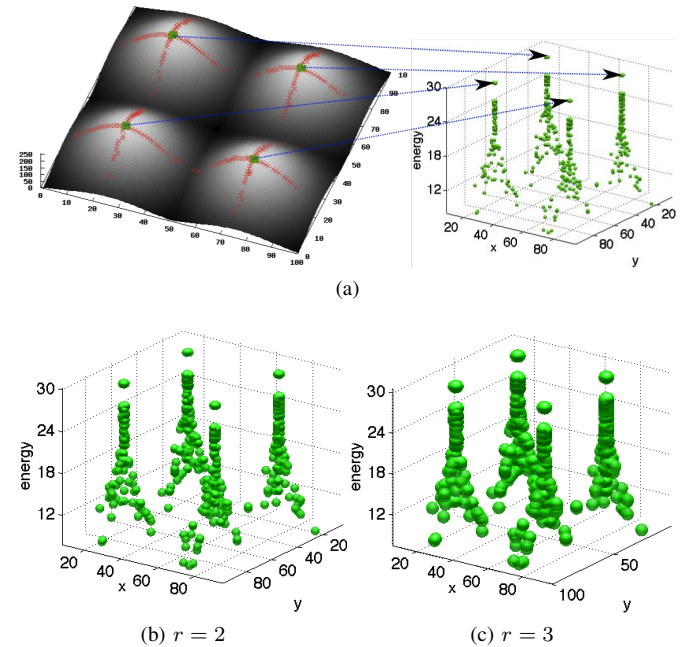

Fig. 1. In (a) artificial crawlers are mapped onto a 3D space by converting the final position and the energy into a point in the surface. (b) e (c) show an illustration of the dilation process for the fractal dimension.

The third contribution of this work is a multiscale texture descriptor based on non-linear diffusion. Many recent texture-analysis methods are developed to extract measures on a single scale. In contrast, we assume that an image texture reveals different structures according to the scale of observation, so that the scale concept of multiscale representation is of crucial importance [38]. Thus, we iteratively represent the original image in a set of new images. Inspired by the work of Yves Meyer [39], where images are combinations of both oscillatory (texture) and geometrical (cartoon) patterns, we get two components for the derivative images. At each iteration step, we estimate the average and deviation of the Bouligand-Minkowski descriptors computed over the two components. We then combine the measures from both components to compose our feature vector. The Bouligand-Minkowski fractal dimension is adopted here due to its precision in quantifying

structural properties. Experimental results over four well-known texture datasets reveal a superior performance of our method. This work was first published in the *Proceedings of the 13th International Conference on Advanced Concepts for Intelligent Vision Systems* with Gabor filters [40]. Later, a new research involving fractal descriptors was submitted to the *Pattern Recognition Letters Journal* [38] and the main ideia of the proposal is presented in Figure 2.
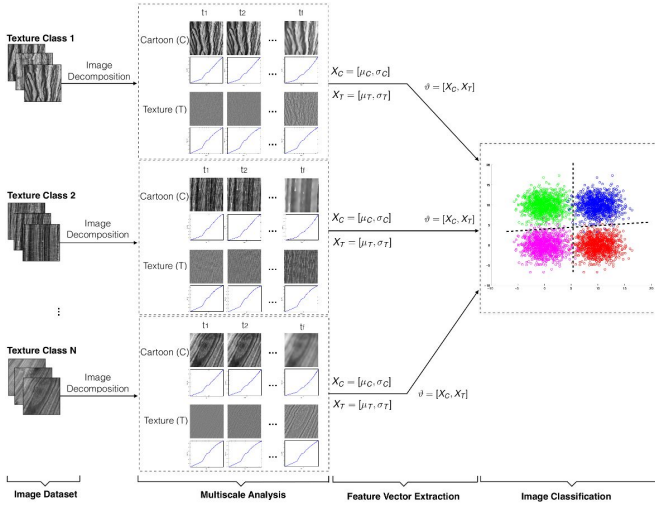

Fig. 2. Schematic representation of our proposal. The dotted-line frames correspond to the images obtained by anisotropic diffusion over the scale space, and t stands for the different scales. The image decomposition is applied to each image of the dataset resulting in two component images: cartoon and texture. Then, the fractal dimension is estimated from each image, and a feature vector is concatenated with the mean and standard deviation of the fractal dimension.

The fourth contribution of this work is the application of the multiscale proposal shown in Figure 2. In this case, we assume that a leaf image presents different details according to the scale of analysis, which is suitable to describe fractal-like structures as observed in leaves. Accordingly, we propose a multiscale fractal descriptor that is applied over derivative images obtained by means of anisotropic diffusion. In our methodology, the gray levels of an image correspond to the energy diffusion at different levels represented in new derivative images. We split each new derivative into geometrical and oscillatory parts. Subsequently, we estimate the Bouligand-Minkowski fractal dimension of each component and combine the features to perform texture classification. Experiments indicate that our approach can successfully identify soybean leaf diseases and can also be used as a front-end application to non-experts or agronomists. In addition, our method was compared to other traditional texture methods showing superiority for recognition of soybean leaf diseases. This work [41] has been integrated to the mobile application called *BioLeaf - Foliar Analysis* [42], which was submitted for software registration at the Brazilian agency National Institute of Industrial Property (INPI). Both the methodology and the mobile application description were submitted to the *Computer Electronics and Agriculture Journal*. Details of the tool are presented in Figure

3.

Fig. 3. Screenshots of the BioLeaf application, and it can be downloaded freely from GooglePlay at https://play.google.com/store/apps/details?id=upvision.bioleaf.

Finally, the fifth contribution of this work is a complex network approach for particle agglomeration analysis in nanoscale images. In this work, instead of assuming that a nanoscale image is a textured surface, we have modeled the nanoparticles like vertices of a graph, while connections are created according to a thresholding for density estimation over a certain radius. For each nanoparticle, we calculate its density. Two particles are linked, defining and edge, only if their distance is smaller than a given radius and its density is higher than a given threshold. This work has been submitted to the *Information Sciences Journal* [43]. Furthermore, this work was integrated into an expert system (see Figure 4), named NanoImage Analyzer, and it was submitted for software registration also at INPI. NanoImage Analyzer can be downloaded freely at http://nanoanalyzer.icmc.usp.br.

III. CONCLUSION

Texture description has always been a challenging task in image analysis and computer vision. Texture analysis methods have emerged as important tools for real-world applications, this is because they can learn patterns from objects or regions with annotated examples. Typically, such methods aim to measure raw image pixels into a discriminant data space. Despite the achievements, effective feature description is still a challenge. In this work, we introduced novel methods for texture description applied over domains ranging from agriculture to nanomaterials. We have achieved promising results, as previously discussed, with the aim of demonstrating that texture, as found in natural settings (leaves and nanoparticles), is of great potential in image analysis and computer vision.

In conclusion, this work departed from the hypothesis that the use of texture information can improve systems that depend on image analysis. We tested this initial assumption over several domains using different proposed methods. Our results, as discussed in the previous section, demonstrated that, indeed, multiscale image representation has potential in enhancing the discriminatory power when the scale is taken

(a) NanoImage Analyzer can be downloaded at http://nanoanalyzer.icmc.usp.br

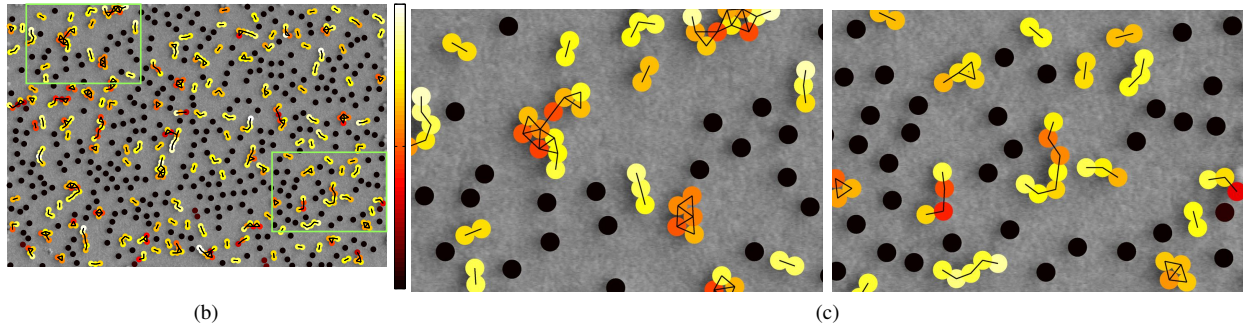(b)   (c)
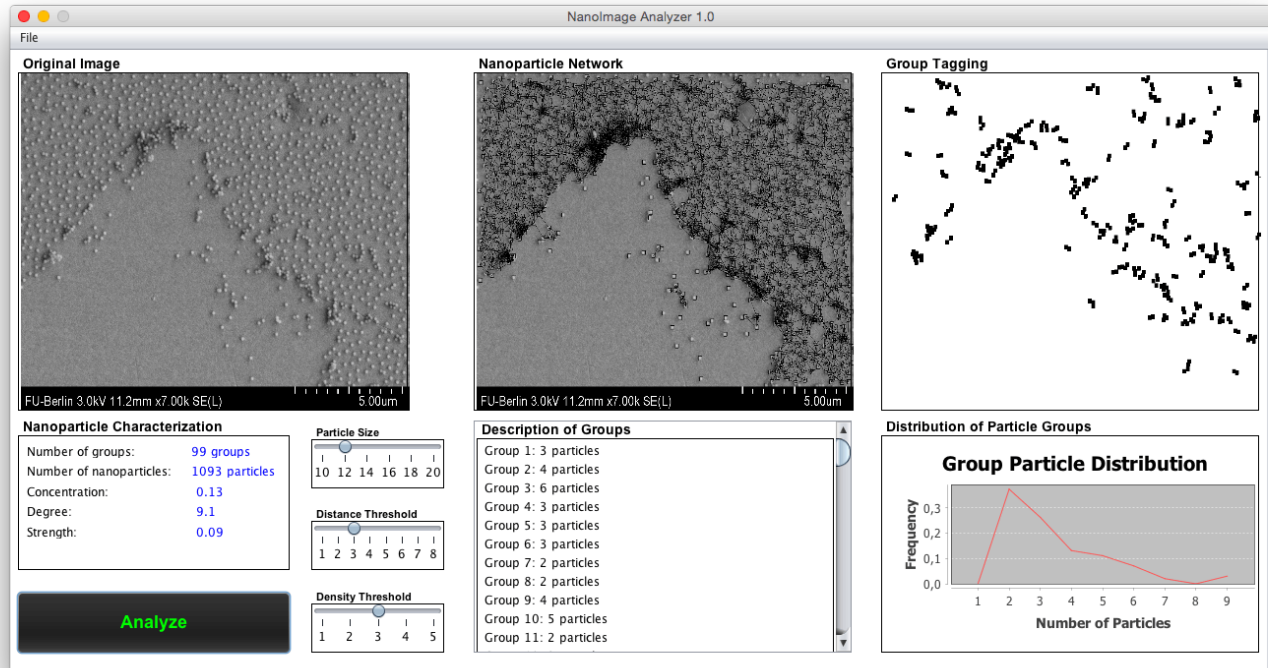
Fig. 4.   (a) Tool NanoImageAnalyzer implemented for analysis of nanoparticles agglomeration in nanoscale images. In second row, we show the nanoparticle image modeled as a complex network proposed in this work. (b) Density of each nanoparticle, represented by the heatmap colors, and connections of the resulting complex network. (c) Zoomed-in regions as indicated in (b).

into account. Future directions of the feature design are lead by advances in deep neural network construction, that has brought a significant breakthrough for feature description.

IV. Software Registration and Publications

The work of my Ph.D. was published in the following refereed publications, and it was submitted, in the form of software registration, to the National Institute of Industrial Property (INPI).

Journal articles

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- MACHADO, B.B., GONCALVES, W.N., ARRUDA, M.S., RODRIGUES, J.F.J. Multiscale fractal descriptors using anisotropic diffusion of Perona-Malik for texture

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Software registration

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