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Improved texture image classification through the use of a corrosion-inspired cellular automaton

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ABSTRACT

In this paper, the problem of classifying synthetic and natural texture images is addressed. To tackle this problem, an innovative method is proposed that combines concepts from corrosion modeling and cellular automata to generate a texture descriptor. The core processes of metal (pitting) corrosion are identified and applied to texture images by incorporating the basic mechanisms of corrosion in the transition function of the cellular automaton. The surface morphology of the image is analyzed before and during the application of the transition function of the cellular automaton. In each iteration the cumulative mass of corroded product is obtained to construct each of the attributes of the texture descriptor. In the final step, this texture descriptor is used for image classification by applying Linear Discriminant Analysis. The method was tested on the well-known Brodatz and Vistex databases. In addition, in order to verify the robustness of the method, its invariance to noise and rotation was tested. To that end, different variants of the original two databases were obtained through addition of noise to and rotation of the images. The results showed that the proposed texture descriptor is effective for texture classification according to the high success rates obtained in all cases. This indicates the potential of employing methods taking inspiration from natural phenomena in other fields.

1. Introduction

The classification of texture images is an important problem in pattern recognition and consequently forms the subject of many research works in this field. Texture is an important image feature with a strong discriminative capability and is therefore widely used in computer vision. Image descriptors for image texture are obtained from the analysis of groups of pixels and the way this analysis is performed is used to classify the different methods of texture analysis. Based on the domain from which the texture feature is extracted, five main categories can be distinguished: structural [1–3], statistical [4], model-based [5–7], spectral [8,9], and agent-based methods [10–12].

This paper proposes a novel texture descriptor constructed by means of a cellular automaton (CA) taking inspiration from the pitting corrosion phenomenon, further on referred to as the Corrosion-Inspired Texture Analysis (CITA) descriptor. The basic mechanisms behind this detrimental reaction which occurs between metals (or alloys) and their environment serve as inspiration to develop a CA-based model. Next, this CA-based model is employed to generate a texture descriptor for classification by treating the image to be classified as a metal surface. The CA-based model, like real corrosion, amplifies existing differences in material and height (in this case grayscale value) so that the biggest contrasts in the original texture image will become more pronounced and smaller contrasts will be nullified. The eroded mass of 'metal' by the progression of pitting corrosion at each iteration is used to generate a texture descriptor that describes the image to be classified. These texture descriptors are then used as feature vectors in a supervised setting to develop a classification method. The effectiveness of this strategy is demonstrated on two texture databases, Brodatz and Vistex, with natural and synthetic textures. In addition, to verify the robustness of the classification method, its invariance to noise and rotation were tested, obtaining satisfactory results.

The main contribution of this work thus lies in demonstrating that a natural phenomenon can be a source of inspiration to develop a

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robust texture descriptor for the classification of both natural and synthetic texture images. Moreover, the proposed method outperforms the state-of-the-art methods in texture analysis, thus contributing to the image analysis field. Our paper is organized as follows. Section 2 describes the basics behind the pitting corrosion phenomenon, while the definition of a CA as well as further explanation of some parts of this definition form the subject of Section 3. The classification method is described in Section 4 and the experimental setup needed to test its efficacy is explained in Section 5. Section 6 presents the results and Section 7 presents the discussion of the study. Finally, the paper is concluded in Section 8.

2. Pitting corrosion

Corrosion is the disintegration of metals (and alloys) into their constituents due to reaction with the environment and is one of the main causes of structural failure in industrial systems, and poses as such an economic problem [13]. Dealing with corrosion is difficult because of its complex nature and the involvement of many variables. Therefore, modeling and simulation could allow for predicting more accurately the corrosion process in time. CA-based models are excellent candidates for modeling corrosion due to their intrinsic simplicity and therefore, since the beginning of the new millennium, attempts are being made to employ these models in the field of corrosion engineering [14–18]. Corrosion is present in a wide range of metals and environments, which points to the universality of this phenomenon. The latter suggests that corrosion does not depend on the details of the underlying mechanism, so that it may be modeled adequately using simple models [19]. Moreover, CA-based models are able to capture the stochasticity of the involved electrochemical reactions at the mesoscopic scale [16].

Pitting corrosion is a very harmful and common form of localized corrosion where all or most of the metal loss occurs concentrated in certain areas. Upon close inspection of the metal surface, pitting can be recognized by the appearance of small holes on the metal surface as shown in Fig. 1. The first step in pitting corrosion is the pit initiation which is the result of impurities or irregularities of the metal surface or the environment, making perfectly polished surfaces more resistant to this type of corrosion. From there on, the acidity inside the pit is maintained by the spatial separation of the cathodic and anodic half-reactions, which creates a potential gradient and electromigration of aggressive anions into the pit (see Fig. 1). As pit growth progresses, different solution compositions develop inside the cavity and the consequent voltage (IR) drop along the metal/electrolyte interface illustrates that the deeper the pit, the lower the pit growth rate [17,21,22].

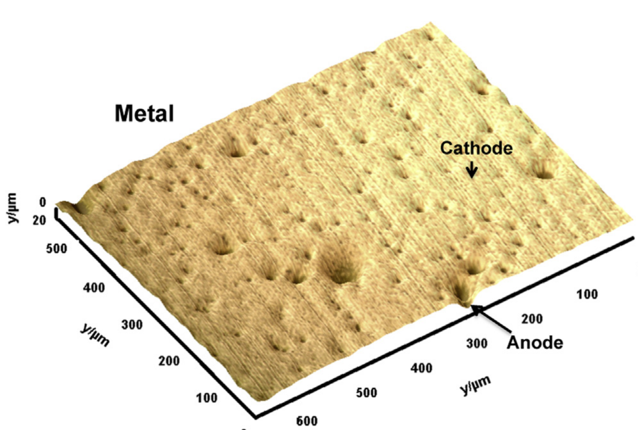

Fig. 1. Pitting corrosion: schematic representation in a metal surface.

3. Cellular automata

CAs are mathematical constructs in which the space, state and time domains are discrete as opposed to partial differential equations (PDE) in which these three domains are continuous [23,24]. The ability of CAs to generate a rich spectrum of sometimes complex spatio-temporal patterns from relatively simple underlying transition functions has led to their successful employment in the modelling of several biological processes [25–30]. Models based on CAs can be seen as an alternative to PDE-based models, to provide researchers with a wider range of modeling tools and, in some complex cases, a solution to problems encountered with some of the more classical modeling methods [31,32].

In this paper, we make use of a homogeneous CA, in which a single transition function, constructed using a combination of knowledge on the pitting corrosion phenomenon and intuition, governs the dynamics of all cells. The following definition of a homogeneous 2D CA is relied upon.

Definition 1 (*Homogeneous 2D cellular automaton*). A homogeneous 2D cellular automaton $\mathcal{C}$ can be represented as

$\mathcal{C} = \langle \mathcal{T}, S, s, N, \Phi \rangle$,

where

(i) $\mathcal{T}$ is a two-dimensional grid of cells c.
(ii) S is a finite set of k states, with $S \subset \mathbb{N}$.
(iii) The output function s yields the state $s(c,t)$ of every cell c at the t-th discrete time step.
(iv) The neighborhood function N determines the neighboring cells of every cell c, including the cell c itself.
(v) The transition function Φ yields the state $s(c,t+1)$ of every cell c at the next time step, based on its state and that of its neighboring cells at the current time step.

For reasons of comprehensiveness, some parts of this definition will be elaborated in the remainder of this section.

3.1. Grid $\mathcal{T}$

In this paper, a finite two-dimensional grid consisting of squares is used, because it has the most straightforward implementation and provides an easy way of linking the cells of $\mathcal{T}$ to the pixels of the texture images to be classified (cfr. infra). Furthermore, an indexing of the cells of a 2D CA is introduced, which is shown in Fig. 2. For a square grid, it holds that $i^* = j^* = \sqrt{|\mathcal{T}|}$.

3.2. Neighborhood function N

Many different neighborhoods can be defined in 2D, the two most important ones being the Moore and the von Neumann neighborhood. The Moore neighborhood of a cell $c_{i,j}$ comprises those cells that share at least a vertex with $c_{i,j}$ (see Fig. 3(a)). The von Neumann neighborhood is a more restricted neighborhood in which only those cells that share an edge with $c_{i,j}$ are considered as neighbors (see Fig. 3(b)).

3.3. Discrete states

Every cell $c_{i,j}$ has one of the k discrete states comprised in the set S. The states of the cells $c_{i,j}$ of $\mathcal{T}$ at $t=0$, i.e. $s(c_{i,j},0)$, constitute the initial condition of $\mathcal{T}$. In this paper, the initial condition of $\mathcal{T}$ is determined by the grayscale value of the different pixels of the corresponding texture image (cfr. infra).