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A new computational approach to cracks quantification from 2D image analysis: Application to micro-cracks description in rocks

Alessio Arena [1], Claudio Delle Piane *, Joel Sarout

CSIRO Earth Science and Resource Engineering, 26, Dick Perry Avenue, Kensington 6151, Western Australia, Australia

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ABSTRACT

In this paper we propose a crack quantification method based on 2D image analysis. This technique is applied to a gray level Scanning Electron Microscope (SEM) images, segmented and converted in Black and White (B/W) images using the Trainable Segmentation plugin of Fiji. Resulting images are processed using a novel Matlab script composed of three different algorithms: the separation algorithm, the filtering and quantification algorithm and the orientation one. Initially the input image is enhanced via 5 morphological processes. The resulting lattice is "cut" into single cracks using 1 pixel-wide bisector lines originated from every node. Cracks are labeled using the connected-component method, then the script computes geometrical parameters, such as width, length, area, aspect ratio and orientation. A filtering is performed using a user-defined value of aspect ratio, followed by a statistical analysis of remaining cracks. In the last part of this paper we discuss about the efficiency of this script, introducing an example of analysis of two datasets with different dimension and resolution; these analyses are performed using a notebook and a high-end professional desktop solution, in order to simulate different working environments.

1. Introduction

2D image analysis in geosciences is mainly focused on the scrutiny of two classes of objects of distinct geometry:

1. Grains, minerals, pores, and all the objects that have a shape traceable to an ellipse. These objects are analyzed for applications including estimates of porosity and permeability (Lock et al., 2002), grain size distribution (Berger et al., 2011), plastic strain and mineral reactions estimations (Delle Piane et al., 2009);
2. Objects described by a linear shape such as cracks, hydrographical elements, roads and others. The analysis of these objects is complicated by their spatial interactions and a separation processing is necessary if the characterization of every single element of the population is required.

In this article we propose a new separation method for 2D linear objects, applied to the study of microcracks in crystalline rocks.

As defined by Simmons and Richter (1976), a microcrack is:

> "*an opening that occurs in rocks and has one or two dimensions smaller than the third. For flat microcracks, one dimension is much less than the other two and the width to length ratio, termed crack aspect ratio, must be less than 10^{-2} and is typically 10^{-3}–10^{-5}. The length typically is of the order of 100 μm or less.*"

Microcracks strongly affect rocks' physical properties, such as permeability (e.g. Fortin et al., 2011; Sarout, 2012), and static/dynamic elastic moduli (e.g. Delle Piane et al., 2011; Heap and Faulkner, 2008; Sarout and Guéguen, 2008); yet there is no uniquely accepted method to precisely quantify the density and geometrical characteristic of such microstructural features.

Automatic crack detection methods have been proposed for structural investigations of building and engineering materials: Dare et al. (2002) introduced a user-guided feature extraction application for the measurement of crack width based on digital images of single cracks in of concrete acquired with a digital camera. Chen and Hutchinson (2010) and Lee et al. (2013) also proposed a framework for the determination of the geometric quantification of surface cracks in concrete using digital images visualizing the evolution of one crack. More recently, Zhu et al. (2011) and Jahanshahi and Masri (2013) presented a method of retrieving the properties of the cracks (orientation and width) from optical images of concrete based on crack detection and crack property retrieval, using image thinning and distance transform techniques. It should be noted however that all of the above

* Corresponding author. Tel.: +61 8 6436 8716.
E-mail addresses: alessio.arena@lithicon.com (A. Arena), claudio.dellepiane@csiro.au (C. Delle Piane), joel.sarout@csiro.au (J. Sarout).

[1] Now at Lithicon Australia Suite 2 Ground floor,73 Northbourne Avenue, Canberra ACT 2600, Australia.

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methodologies were specifically developed for field applications focused on the detection of macroscopic surface cracks in concrete visualized using a digital camera; as such they are better suited for the recognition and characterization of a limited number of non interacting cracks per field of view.

Microcracks in crystalline rocks are better visualized by means of optical or electron microscopy and generally constitute a network of interacting segment within a visualized field of view requiring a careful separation procedure for the statistical analysis of a large population of objects.

Most of the approaches used for this analysis tried to bypass the problem of cracks separation; some examples are:

- Mamtani et al. (2012) based on the analysis of the fractal geometry of the cracks pattern.
- Chen et al. (2001) computed the average length of cracks by estimating the number of elements and the total length of the lattice.
- DeVasto et al. (2012) used fitting rectangles based on the Multiple Ferret Method (Wang, 2006).

The work of Ito et al. (2002) was probably the first attempt to separate single cracks based on the identification of the nodes of the skeletonized pattern. These nodes were subsequently used for tracing and labeling the cracks. However, the skeletonization process used to perform this operation alters the geometry of the cracks.

Another approach suggested by Le Roux et al. (2013) consists in identifying and dilating the nodes of the crack pattern to separate out the cracks. The nodes are subsequently subtracted from the original black and white (B/W) image. The remaining of the image is then labeled using the "connected-component method" (Han and Wagner, 1990; Samet and Tamminen, 1988).

We propose a new quantification method for the identification of cracks and microcracks, based on an improved version of the separation algorithm originally suggested by Le Roux et al. (2013).

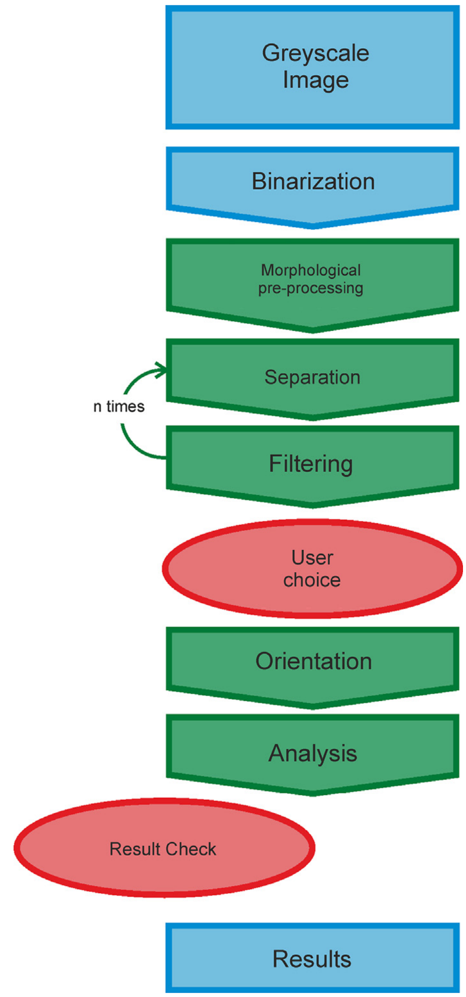

Fig. 1. Flowchart of the crack detection and analysis methodology from 2D images.

2. Methodology

The new method is summarized in Fig. 1 and has been implemented in the *Matlab*® environment. First, an 8-bit image of a polished rock surface, collected with a Scanning Electron Microscope (SEM), is converted into a binary image using the Trainable Segmentation method (Kaynig et al., 2010) available in *ImageJ* (plug-in developed by Schindelin et al., 2012). The binarized image is then loaded into *Matlab* and subjected to a morphological pre-processing. The resulting image is then segmented using bisecting lines originated from branch points, the objects are extracted and then filtered according to user defined parameters; this step is reiterated by changing the region considered during the generation of bisectors in order to achieve a balance between interference among objects and angular resolution. Next, the distributions of orientation, length, width and aspect ratio of the cracks are computed. The user can supervise the results, delete specific objects not relevant for the intended application (e.g. twin lamellae, dust particles, surface scratches) before the final results are displayed. Each processing step is detailed in a separate section below. Additional flowcharts detailing the sequence of single operations for each step are also reported in the Appendices.

2.1. Binarization

First, an 8-bit grayscale SEM image is binarized to yield a black and white image where the solid phase is black and the "empty" phase is white (pores, microcracks etc). The simplest way to perform this operation is by applying a threshold to the gray level histogram. This can be done manually or by applying automatic thresholding algorithms such as the Otsu method (Otsu, 1979; Stanekova and Lapin, 2012). The so-called Trainable Segmentation method, available with the software *Fiji* (*ImageJ* based) (Schindelin et al., 2012), is used in our approach: the user "trains" the software to differentiate and classify different portions of the image by drawing lines, thus collecting information on pixels' gray level and their spatial variation. The advantage of this method is that the operator helps to finely discriminate two or more sets of pixels with different gray levels and/or different gradients by simply drawing a reasonable number of lines used to collect the necessary information. This is particularly critical in conditions of non-uniform illumination of an image where purely automatic algorithm might fail or induce biases.

2.2. Morphological processing

The binarized image (Fig. 2a) is used as input for the Matlab script where morphological algorithms are applied to it. These morphological processing are:

- *Diagonal fill*: this is based on the pixel connectivity theory (Pratt, 2001), widely used in image analysis. In a 3×3 pixels grid the center pixel is considered connected with the neighbor ones if these have the same value; while defining the connection we can consider only the four pixels that occupy the