Computers & Geosciences 86 (2016) 64–74

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Case study

Fast multiple-point simulation using a data-driven path and an efficient gradient-based search

Mohammad J. Abdollahifard

Department of Electrical Engineering, Tafersh University, Tafresh, Iran

ARTICLE INFO

Article history:
Received 24 May 2015
Received in revised form
14 September 2015
Accepted 15 October 2015
Available online 17 October 2015

Keywords:
Geostatistical modeling
Texture synthesis
MPS simulation

ABSTRACT

Multiple-point geostatistics has recently attracted significant attention for modeling different environmental variables. These methods employ the patterns of a training image (TI) to complete a simulation grid (SG), resulting in realizations with good spatial continuity and structural properties. Most existing multiple-point statistics (MPS) methods scan the SG in a random or raster order. In this paper, a new method is presented with a data-driven scanning path giving high priority to pixels with high gradient magnitude. As a result, the image edges are synthesized first, resulting in better connectivity preservation. Although MPS methods usually produce promising results compared to traditional variogram-based modeling, their further development is somehow limited by their excessive computational burden. An efficient search space reduction method, consistent with the proposed ordering scheme, is also presented in this paper. Experiments on different geological fields show results comparable to the state-of-the-art with a significant improvement in CPU time.

1. Introduction

Multiple-point statistics (MPS) simulation is a spatial modeling technique which has recently attracted significant attention for characterization of different spatial variables. It relies on training images (TIs) for modeling the spatial variability of environmental variables (Guardiano and Srivastava, 1993).

The modeling of subsurface behavior is usually a difficult problem, due to the presence of complicated structures formed by sedimentological and erosional processes (Huysmans and Dassargues, 2009). Traditional variogram-based modeling approaches are not so efficient in reproduction of realistically complex geological structures (Journel and Zhang, 2006; Schlüter and Vogel, 2011). Object-based modeling methods are useful in simulating complex structures, but they lack flexibility in data conditioning (Michael et al., 2010). MPS simulation methods are capable of handling complex structures and conditioning constraints simultaneously. However, they suffer from some disadvantages including their heavy computational burden, the difficulty of selecting a representative and adequate training image specifically when enough information is not available for such a decision (Pyrcz et al., 2008), and the difficulty in TI parametrization (Suzuki and Caers, 2008).

MPS simulation proceeds by sampling from the conditional probability distribution function (cpdf) at different SG nodes conditioned to hard data and previously simulated data. This is done by extracting a data-event from the SG and searching the data-base of TI patterns to find a similar pattern and pasting the data from the found pattern into the SG. While pixel-based methods fill only one pixel in each step, patch-based methods fill one patch at a time, resulting in faster simulation (Arpat and Caers, 2007).

To further increase the simulation speed, some researchers suggested to cluster the pattern data-base into a limited number of clusters and compare the data-event only with the cluster representatives (Zhang et al., 2006; Honarkhah and Caers, 2010; Abdollahifard and Faez, 2013). Such methods usually require intensive pre-computations.

Instead of searching a data-base of patterns, Mariethoz et al. (2010) suggested to work directly with the TI. To reduce the excessive computational burden of this approach, Rezaee et al. (2013) suggested pasting a bunch of nodes in each step, and Abdollahifard and Faez (2013a) suggested using an approximate gradient-descent template matching method.

Recently it has been realized that MPS simulation algorithms are similar in many ways to techniques developed for texture synthesis in computer graphics (Mariethoz and Lefebvre, 2014). Tahmasebi et al. (2012) followed the line of Efros and Leung (1999) by adopting a raster scanning path for simulation. Following the image quilting (IQ) idea of Efros and Freeman (2001), Mahmud et al. (2014) suggested to find a minimum error boundary cut between subsequent patches resulting in seamless realizations with very good spatial continuity. Markov mesh models are also

E-mail address: mj.abdollahi@tafreshu.ac.ir

http://dx.doi.org/10.1016/j.cageo.2015.10.010

employed for geostatistical modeling (Daly, 2005; Kjønsberg and Kolbjørnsen, 2008; Stien and Kolbjørnsen, 2011).

While in most MPS simulation methods the SG is scanned in a random or raster order, the effect of attentive path selection has been tested in the computer graphics community resulting in remarkable improvements in pattern connectivity (Criminisi et al., 2004). Inspired by this work, in this paper a Fast Prioritized SIMulation (FPSIM) method is proposed which assigns priorities to SG nodes and selects the node with the highest priority as a new node on the path.

By assigning high priority to pixels having high gradient magnitude, the image edges are synthesized under minimal constraints resulting in improved connectivity patterns. In order to achieve better conditioning we suggest to include the location of hard conditioning data in the computation of priorities as well. It should be noted that since the proposed algorithm is a patch-based method, it synthesizes the low-gradient pixels around the high-gradient point located at the center of the patch. As a result, the method is capable of preserving the image proportions by using large enough patches.

Informed simulation paths based on the information obtained from observed data were previously exploited in MPS simulation (Liu and Journel, 2004; Eskandaridalvand and Srinivasan, 2010). Furthermore, Renard et al. (2011) proposed a method to condition stochastic simulations of lithofacies to connectivity information available before starting the simulation process. In this paper no connectivity information is assumed to be available ahead of time. Instead, the algorithm attempts to achieve better conditioning and mimic the connectivity patterns of the TI by attentive path selection and continuous update of the priority function. It should be noted that the proposed prioritization is applicable to many existing patch-based simulation methods.

Furthermore, in this paper a new gradient based search algorithm is also proposed which reduces the search space up to hundreds of times. By considering the image gradient as an important factor in determining the priority, most of selected data-events have high gradient values in their central pixel. Given the gradient vector in the central pixel, the search space can be confined from the whole TI to templates with comparable gradient in their center.

This paper is organized as follows. In Section 2 the details of the proposed method are presented along with reasons on its importance and usefulness. In Section 3 the algorithm is tested and analyzed on a number of test cases. Finally we conclude in Section 4.

2. Methodology

In MPS simulation methods, an incomplete simulation grid is completed using patterns of a training image (Fig. 1). The simulation proceeds by scanning the SG nodes in a specific order. For each node, a data-event is extracted around the node, then the pattern data-base is searched to find a match, and finally a piece of data is transferred from the found pattern to the SG. The contributions of this paper are twofold. First, it is shown that the order of scanning the nodes has significant effect on simulation quality, and a prioritization method is presented for path selection (Section 2.1). Second, an efficient method for confining the search space and reducing the computational complexity is proposed (Section 2.2). It should be noted that the proposed search method does not provide remarkable performance in general template matching problems. However, as will be discussed later it works very well for patches selected through the proposed prioritization. Therefore, the two advances proposed in this paper are by no means independent.

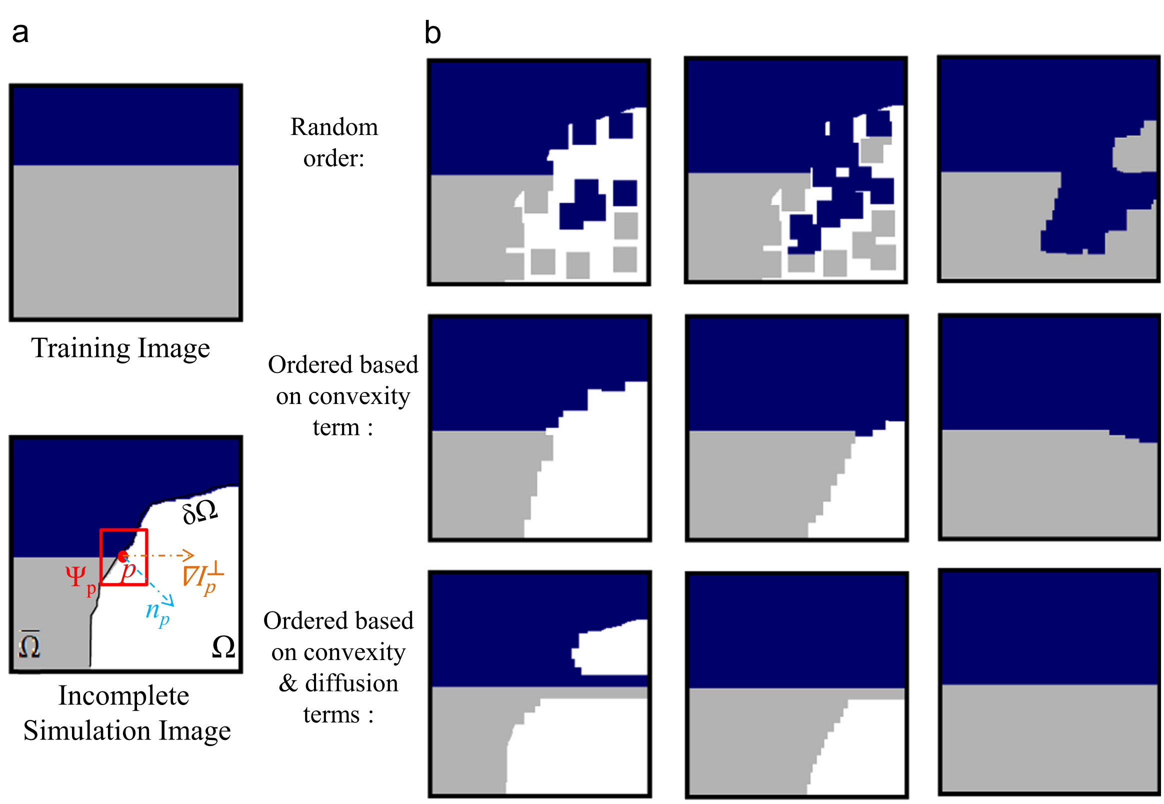

Fig. 1. (a) A simple TI along with an incomplete SG. (b) The completion progress using three different ordering scenarios. First row: random order, second row: ordered based on priorities defined using only the convexity term, and third row: ordered based on priorities defined using Eq. (3).