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Towards a voxel-based geographic automata for the simulation of geospatial processes

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ABSTRACT

Many geographic processes evolve in a three dimensional space and time continuum. However, when they are represented with the aid of geographic information systems (GIS) or geosimulation models they are modelled in a framework of two-dimensional space with an added temporal component. The objective of this study is to propose the design and implementation of voxel-based automata as a methodological approach for representing spatial processes evolving in the four-dimensional (4D) space–time domain. Similar to geographic automata models which are developed to capture and forecast geospatial processes that change in a two-dimensional spatial framework using cells (raster geospatial data), voxel automata rely on the automata theory and use three-dimensional volumetric units (voxels). Transition rules have been developed to represent various spatial processes which range from the movement of an object in 3D to the diffusion of airborne particles and landslide simulation. In addition, the proposed 4D models demonstrate that complex processes can be readily reproduced from simple transition functions without complex methodological approaches. The voxel-based automata approach provides a unique basis to model geospatial processes in 4D for the purpose of improving representation, analysis and understanding their spatiotemporal dynamics. This study contributes to the advancement of the concepts and framework of 4D GIS.

1. Introduction

Geographic automata (Torrens and Benenson, 2005) provide a flexible and adaptable method for simulating a wide range of geospatial phenomena whose spatiotemporal dynamics can be represented using the theory of complex systems. For the most part, however, the methodology has been limited to the two-dimensional perspective of representing geographic processes with the cellular automata models (Torrens and O'Sullivan, 2001). This is in part due to the simplicity of the cellular automata (CA) formalism in representing complex geospatial processes as well as the relative ease of integrating them with geographic information systems (GIS), remotely sensed data and other geospatial information. Besides the limited number of multi-dimensional modelling tools available in the field of Geographic Information Science (GIScience), the geospatial data used in contemporary GIS applications are also formatted according to the raster or vector models, which are both planimetric in their perspective of the real world. In these data models the three-dimensional nature of the geographic space is abstracted in such a way that, for example, the elevation or the temporal dimension, is modelled as an attribute of a location represented by two geographic coordinates (Chrisman, 1997). Thus, continuous phenomena are traditionally represented as an ordered set of independent snapshots, or as a space–time composite layer or as a three-dimensional spatiotemporal structure (Couclelis, 1999). Fully integrated space–time modelling is still a challenge in GIS but there are ongoing efforts to develop frameworks for modelling dynamic phenomena (Plumejeaud et al., 2011; Van de Weghe et al., 2014; Yi et al., 2014). This study proposes an extension of geographic automata systems based on complex systems theory to represent multi-dimensional spatial processes that evolve in the four-dimensional space–time continuum.

First developed by Stanislaw Ulam, the scientific study of CA models was initiated by John von Neumann when he applied them in the investigation of the nature of self-reproducing biological systems (von Neumann, 1966). Later on they were popularized by the publication and eventual widespread use of Conway's game of life (McIntosh, 2010). They are particularly well suited to the study of

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complex systems on the basis that from the application of simple rules of interaction at a local level, there can emerge order and patterns that are vastly complex and often unpredictable (Ilachinski, 2001; Wolfram, 2002; Cotsaftis, 2009). Well specified CA models have been used to generate and study complex patterns and behaviour and over the last two decades they have been applied in various ways to simulate the complexity of dynamic geographic processes (Couclelis, 1985; Batty, 1997; White et al., 1997; Clarke and Gaydos, 1998; Berjak and Hearne, 2002; Benenson and Torrens, 2004; Rothman and Zaleski, 2004). They use discrete spatial elements (cells or rasters) which are undergoing either deterministic or stochastic (non-deterministic) local interactions (Rabin, 1963; Grassberger, 1984). For deterministic automata, the local interactions are actualized with the aid of transition functions that rely on the existing conditions of the neighbourhood to cause a specific outcome at the next iteration (White and Engelen, 1993). Typically, the transition functions operate in such a way that for a given local neighbourhood configuration, a specific change in state may be applied to the cell at the centre of that neighbourhood. On the other hand, stochastic automata are less restrictive by allowing the state of the central cell at the next iteration to be selected from a range of possible outcomes given a specific neighbourhood configuration (Hopcroft, 2007). Moreover, the transition functions that are used to define these local interactions fall into three broad categories, namely, totalistic, semi-totalistic and non-totalistic automata functions. In totalistic CA, the transition functions depend on the simple summation or average of the cell values in the neighbourhood; in semi-totalistic automata the transitions depend on the state of the central cell as well as the summation of neighbors; while in the non-totalistic CA the cell values change based on the positioning of the other cell values in the neighbourhood (Wolfram, 1983). This is a bottom-up approach to conceptualizing transition rules. However, some studies have used a top-down approach in defining the transition functions in 3D CA models by typically using differential equations to simulate the behaviour of natural phenomena such as gaseous diffusion (Weimar, 2002). Essentially this implies that a continuous function, the differential equation, is used in the discrete environment of CA in order to arrive at an approximate representation of a continuous phenomenon (Gobron et al., 2011). Moreover, the models assume a priori knowledge of the phenomena, which is an element that is in direct contrast to the study of emergent patterns based on the logical interaction of multiple components at the local level. Although the top-down approach is less tedious to implement, the selection of the most suitable approach will often depend on the nature of the phenomenon and the objectives of the study. In this study, the bottom-up approach is used in consideration of the broader objective of exploring natural phenomena as a generative process around proximal elements, an idea that is closely connected to Tobler's first law of geography (Tobler, 1970). The transition rules used follow this approach to simulate the different processes as they evolve over space and time.

Using simple rules to govern the local interactions at specific time intervals, it has been shown that as the states of the spatial elements change, the system as a whole evolves and gives rise to emerging patterns and self-organizing behaviour which are all general characteristics of complex systems (Lansing, 2003; Holland, 2006). In particular, the application of geographic automata is well suited to complex systems modelling because the phenomena are themselves inherently spatial in character, time dependent, and exhibit a complexity of pattern formation resulting from the various interactions of the systems' components. Although the key concepts of the classical CA formalism have been extended to develop geographic automata models to represent geographic processes and to study complexity, most of these automata models are limited to the two-dimensional of spatial perspective (Benenson and Torrens, 2004). In reality, however, geographic processes occur in a four-dimensional (4D) continuum and many of these are best represented with the aid of the three dimensions of space with time being the fourth one. For example, urban land use change has been modelled and analysed using two-dimensional spatial data; however, other growth processes like fire spread, particle diffusion and 3D landscape surface change would be more insightful when modelled using a 3D spatial framework.

The main objective of this study is to develop a voxel-based automata modelling approach, as an extension of the theory of geographic automata systems, capable of simulating spatiotemporal processes in the four dimensions of the space–time domain. The voxel as a volumetric element is used to represent the smallest 3D spatial unit that changes its state based on the functioning of the automaton's transition rules. For the purposes of the automata simulation, the form of the voxel can be a tetrahedron, cube or a hexahedron provided it has both translational and rotational symmetries. By designing and applying local transition rules, the voxel automata approach is used to generate 3D spatial patterns that closely resemble those of geospatial phenomena as they evolve in the four dimensions of the space–time domain.

2. Literature overview

Both 2D and 3D space can be modelled from either a field-based perspective or an object-based perspective (Frank, 1992; Galton, 2009) and it is also possible to amalgamate these two approaches in the representation of spatiotemporal phenomena (Kjenstad, 2006; Voudouris, 2010). In the field-based perspective, the cells, rasters or voxels are assigned a specific attribute value that represents the phenomenon at that location while in the object-based perspective each voxel has a persistent object identifier in addition to the attribute elements. The object-based perspective allows for the construction of 3D spatial topology relationships and queries which are important in the analysis of agent-based model simulation outcomes. As the focus of this study is on the use of voxels in automata simulations the *methods* use the field-based perspective to represent space and 3D map algebra can be used to further analyze the model's outcomes. The phenomenon's temporal component is modelled using the automata's time step.

In geography, CA were proposed by Tobler (1979) as a suitable modelling approach to represent spatial-temporal change and have since found widespread use in modelling processes such as land use change. For the most part, the two-dimensional CA models for geographic processes operate on grid spaces with uniform tessellations due to the prevalence and complementarity of the raster geospatial data format with geographic information systems (Clarke and Gaydos, 1998; Stocks and Wise, 2000). However, this is not a strict requirement and work has been done using irregular spatial tessellations (Semboloni, 1997; Shi and Pang, 2000; Stevens and Dragicevic, 2007) or vector-based CA (Moreno et al., 2008).

The two-dimensional CA models have been used extensively to simulate land use and regional change, for example by Batty and Xie (1994), White et al. (1997), Clarke and Gaydos (1998), Lau and Kam (2005) and Kocabas and Dragicevic (2007). In addition, they have been used to represent various environmental processes such as pollutant diffusion (Guariso and Maniezzo, 1992); physical processes such as landslides (Di Gregorio et al., 1999; Lai and Dragicevic, 2011) and snow avalanches (Barpi, 2007); ecological processes such as insect forest infestations (Bone et al., 2006); the spread of forest fires (Berjak and Hearne, 2002; Yassemi et al., 2008); and the dynamics of marine animals (Vabø and Nøttestad, 1997). All of these processes operate in 3D spaces over extended temporal durations and should be simulated with models designed to study and analyze the 4D space–time domain. A 4D modelling approach is useful because it represents a process'