ARTICLE IN PRESS

Advances in Engineering Software xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Research paper

Real-time visualization of 3D terrains and subsurface geological structures

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ARTICLE INFO

Keywords:
Terrain modeling
Volume rendering
GPU Memory management
Stack-based representation of terrains

ABSTRACT

Geological structures, both at the surface and subsurface levels, are typically represented by means of voxel data. This model presents a major drawback: its large storage requirements. In this paper, we address this problem and propose the use of a stack-based representation for geological surface-subsurface structures. Although this representation has been mainly used for volumetric terrain visualization in previous works, it has been used as an auxiliary data structure. Therefore, our main contribution in this work is its use as a first-class representation for both processing and visualization of surface and subsurface information. The proposed solution provides real-time visualization of volumetric terrains and subsurface geological structures represented as stacks using a compact data representation in the GPU. Different GPU memory implementations of the stacks have been described, discussing the tradeoffs between performance and storage efficiency. We also introduce a novel algorithm for the calculation of the surface normal vectors using a hybrid object-image space strategy. Moreover, important features for geoscientific applications such as visualization of boreholes or geological cross sections, and selective attenuation of strata have also been implemented in a straightforward way.

1. Introduction

Terrain modeling and visualization are fundamental aspects of many geoscientific applications in fields like Geomorphology or Stratigraphy, but are also important in non-scientific areas such as films or videogames. The representation of terrains is usually carried out by means of the modeling of its geometry (surface and optionally subsurface) and an enhancement of the appearance by including shading, different colors for different features (e.g., elevation, materials, etc.), or aerial/satellite imagery. Traditionally, digital elevation models (DEM) have been the preferred method for terrain surface modeling. But terrain raster representation using this 2.5D model is limited to one single elevation value for each cell. As a result, it is unsuitable for modeling complex surface/subsurface features like natural overhangs or caves. Moreover, in recent years the improvement in data acquisition and generation methods [1,2] has provided accurate subsurface data, such as statigraphic information or location of groundwater, cavities or fractures, which require more general models than a simple DEM. This kind of data is usually represented by means of voxel models [3]. Voxel models consist of a regular 3D space partition where each cubic element (called voxel, from volumetric element) represents a single value within the grid. Voxel models are ubiquitous in many fields such as medical imaging [4], scientific visualization and simulation [5], engineering applications [6] or gaming. It has also been widely used in many geoscientific works [7] and adopted by 3D GIS software such as GRASS [8] and Mapinfo Engage [9]. However, this volumetric representation raises the problem of a large memory consumption, which can be a relevant factor during the processing and visualization of high resolution models.

A more efficient representation is to extend DEMs to store in each cell a sequence of vertical intervals of the same material or attribute instead of a single elevation value. This is a straightforward way to compact stacks of voxels with a common attribute and the same X–Y coordinate. This is not a novel idea; indeed Benes and Forsbach already introduced the *Stack-Based Representation of Terrains* (SBRT) in the context of modeling terrain erosion [10]. A main strength of this representation is that it keeps the simplicity of DEMs, making it possible to implement raster operations in an easy way. Having a simple representation that serves both for implementing raster operations on the terrain and for efficient rendering is important for many geoscientific applications.

Based on this representation, we present a real-time framework for visualization of terrain and geological structures by adapting the volume rendering algorithm based on raycasting. Our visualization method allows performing cross sections on the terrain, attenuation of stratigraphic layers or selective visualization of boreholes, among other operations. In order to achieve interactive frame rates we have implemented the volume rendering in the GPU, encoding the stacks of materials in a very compact way as a set of textures and buffers in GPU memory. This avoids expensive data transfers between GPU and CPU

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http://dx.doi.org/10.1016/j.advengsoft.2017.10.002
Received 5 May 2017; Received in revised form 22 September 2017; Accepted 8 October 2017

that can be a bottleneck in a visualization system.

We want to highlight that the SBRT is not only a convenient representation for real-time visualization of surface and subsurface of the Earth. We are also working on the definition of different geomodel conversion methods (to and from voxel models, DEMs or MultiDEMs), spatial operators, resampling methods and advanced terrain analysis. Most of these operations can be defined by adapting the Map Algebra of Tomlin [11], widely used in geospatial applications, to the SBRT. For instance, resampling can be implemented as a particular case of the *local operations* defined in this algebra. But this is still a work in progress. The design and implementation of these operations will be discussed in subsequent papers.

Through this paper we distinguish between volumetric/3D terrain and geological/subsurface structures. The first term concerns the boundaries of the terrain, i.e., the surface and elements such as caves or overhangs, whilst the second term involves the different geological features of the subsurface such as materials or aquifers.

Thus, the novel contributions of this paper are:

- A real-time rendering method for the visualization of volumetric terrains and geological structures, using a stack-based representation of terrains as main data structure.
- A comparison among different implementations in GPU of the representation proposed.
- The implementation of useful visual features for geoscientific applications in order to validate the use of the representation.
- An efficient and simple method to calculate normal surface vectors in image space.

The remainder of this paper is organized as follows. Section 2 provides a review of the existing literature. In Section 3, the stack-based representation for geomodels is outlined. Section 4 is focused on the explanation of the pipeline followed in our rendering algorithm, as well as it depicts several features of our framework. An analysis of a set of memory layouts proposed is discussed in Section 5. Finally, we conclude our work in Section 6.

2. Related work

Traditionally, spatial data in GIS are represented by vector and raster data types. 3D GIS commonly takes boundary representation models (B-rep) besides 3D lines and points, and voxel models as the natural 3D extension of 2D vector and raster data types respectively [12].

B-rep models have been represented by several structures. Irregular Networks are based on the use of the simplest geometric structures for each dimension, called simplexes. Therefore, Triangular Irregular Networks (TINs) are made up of 2D simplexes (i.e. triangles) and Tetrahedronised Irregular Networks (TENs) consist of a set of 3D simplexes (i.e. tetrahedrons). TINs have been used for the representation of geological structures in the form of surfaces. For instance, Lemon and Jones [13] used triangular surfaces in order to delimit the horizons between the strata identified from boreholes data. TINs have also been used for modeling free-form stratigraphic layers [14]

Regarding TEN representation, it was used by Caumon et al. for integrating geological formation data, provided by remote sensing images (stratigraphic horizons), and digital elevation models [15]. Another work presented a methodology for mesh generation in subsurface simulation modeling using finite elements [16]. An important drawback of these data structures is that checking and ensuring their topology consistency is a non-trivial task [17]. Data structures based on hierarchical decomposition such as generalized maps [18], or focusing on the representation of boreholes such as generalized tri-prism [19] have been proposed to avoid this problem.

In reference to terrain representation using voxels, Jones et al., estimated the curvature in rock weathering using voxel grids [20], whereas in [21] a voxel model was constructed from geological data acquired from using Airbone Electromagnetics (AEM). More recently, a tool for generating voxel models obtained from parametrized data provided by a series of geological surfaces has been presented [22].

Usually, the visualization of these models has been done by converting them to triangle meshes as a first step [23–25]. This approach has a couple of significant drawbacks in terrain visualization applications: (1) the large amount of geometry that has to be processed by the GPU and (2) the difficulty of rendering internal elements. For these reasons, some researchers have focused on the visualization through *Direct Volume Rendering* (DVR) techniques [26]. In this field, we can find works performing raycasting [27,28], representing volumes as multiscale vectors [29], by diffusion surfaces [30] or from implicit representations [31]. There are also works focusing on the surface of the terrain, without rendering volumetric features [32–34].

For a more comprehensive review of volumetric terrain and subsurface modeling state of art, we refer to the survey of Natali et al. [35].

So far the stack-based terrain representation and its variations have been used in a few scientific works, mostly focusing on the visualization at the ground level. Benes and Forsbach, precursors of this model, used it to simulate thermal erosion in a terrain. In this work, they visualized the surface of the terrain by generating a height map [10]. Peytavie et al. [36] got a more realistic visualization by proposing a hybrid model in which a stack-based representation (referred to as *material layer stacks representation*) serves as support for generating an implicit surface for rendering. Also, some sculpting and erosion terrain tools were added. This work was extended by Loffler et al. [37] by creating a pipeline for the acceleration of this surface generation. Their system achieves real-time frame rates in the rendering of high resolution models. Natali et al. [28] were the first to take advantage of this structure for modeling subsurface geological structures. In their work, they present a system for sketching and visualization of geomodels to help geologists to teach geological concepts. Their system works as follows: an expert sketches a series of material layers and geological elements (e.g. rivers, lakes, etc.), which are converted into multiple height maps for rendering. Unfortunately, the use of height maps only allows elements that can be represented in 2.5D, excluding features like overhangs, caves, aquifers or petroleum reservoirs.

In the previous approaches, the stack-based model plays a secondary role, to visualize complex terrain structures or erosion processes at the ground level or as an intermediate representation generated from a logical model. In this paper we propose to use the stack-based model as a primary representation for geological structures both at the surface and subsurface levels, describing a direct real time rendering algorithm in GPU with a good visual quality for scientific applications.

3. Stack-based terrain representation

This terrain representation can be considered as a generalization of common height maps. As described above, whereas height maps contain a single value for each X–Y coordinate position, stack-based representation stores a stack of intervals. Each of these intervals is formed by a start height and the attribute within it, similar to a run-length encoding scheme (Fig. 1).

The stack-based terrain representation is a natural representation for data generated by borehole logging. A borehole provides a top to bottom sequence of materials at a given X–Y position (Fig. 2). A common way to obtain a geomodel of the subsurface is by means of an interpolation/extrapolation procedure of the boreholes samples, obtaining a layer-cake model as a result [38]. This generated model fits perfectly with the stack-based representation since each cell of the terrain can store a single borehole record as a stack, including both materials and height of the geological formations (e.g. water, petroleum, clay, rock, etc.) and geological properties (e.g. density, permeability, resistivity, etc.).

Although the stack-based representation is appropriate for 3D