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A view-dependent spatiotemporal saliency-driven approach for time varying volumetric data in geovisualization

Jing Li [a,*], Tong Zhang [b,c], David W.S. Wong [d], Meghan Mooney [a]

[a] Department of Geography and the Environment, University of Denver, Denver, CO, USA
[b] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China
[c] Collaborative Innovation Center of Geospatial Technology, Wuhan 430079, China
[d] Department of Geography and Geoinformation Science, George Mason University, Fairfax, VA, USA

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ABSTRACT

Geospatial datasets from satellite observations and model simulations are becoming more accessible. These spatiotemporal datasets are relatively massive for visualization to support advanced analysis and decision making. A challenge to visualizing massive geospatial datasets is identifying critical spatial and temporal changes reflected in the data while maintaining high interactive rendering speed, even when data are accessed remotely. We propose a view-dependent spatiotemporal saliency-driven approach that facilitates the discovery of regions showing high levels of spatiotemporal variability and reduces the rendering intensity of interactive visualization. Our method is based on a novel definition of data saliency, a spatiotemporal tree structure to store visual saliency values, as well as a saliency-driven view-dependent level-of-detail (LOD) control. To demonstrate its applicability, we have implemented the approach with an open-source remote visualization package and conducted experiments with spatiotemporal datasets produced by a regional dust storm simulation model. The results show that the proposed method may not be outstanding in some specific situations, but it consistently performs very well across different settings according to different criteria.

1. Introduction

Time-varying volumetric datasets from satellite observations and model simulations are becoming more available and accessible, and they can be used to support various types of advanced analysis and decision making (Andrienko et al., 2007; Yang, Wu, Huang, Li, & Li, 2011). A challenge to visualizing these dynamic volumetric datasets is handling the computational intensity required for data processing and rendering, particularly when the data are accessed remotely (Lamberti & Sanna, 2007). Visualizing massive datasets with remote access is challenging, as efficient rendering is a prerequisite (Stegmaier, Diepstraten, Weiler, & Ertl, 2003). Examples of remote visualization packages and tools are UVCDAT (LLNL, 2015), AWIPS (Unidata, 2015), and ParaView (Kitware, 2015).

Although remote visualization systems are available, they have not been widely adopted to visualize time-varying volumetric datasets because they are not tailored to facilitate the discovery of spatiotemporal changes of volumetric datasets, an important objective of geovisualization (MacEachren & Kraak, 2001; Wong et al., 2014). To effectively identify areas of changes, the spatiotemporal heterogeneity of data needs to be considered (Andrienko, Andrienko, Dykes, Fabrikant, & Wachowicz, 2008), which is often not considered in existing remote visualization solutions. Regions with high degrees of variability and showing changes over time should be of great interest to users (Erwig, 2004). During the interactive visualization process, heterogeneous regions should be rendered at finer spatial resolutions and highlighted through enhanced visual representations (e.g., enhanced local contrast) so that these regions can easily be recognized by users (*effectiveness*). Visual enhancements should also not significantly affect the overall rendering speed to hamper interactivity (*efficiency*). Although current techniques address either the efficiency *or* effectiveness of rendering, they do not address both issues together to enhance interactive visualization of spatiotemporal volumetric data in a remote-access setting.

The aim of this article is to propose a method toward building an efficient and effective remote visualization framework for dynamic volumetric data. This method is based on the concept of information saliency. In computer vision, saliency measures how certain parts of a scene stand out as compared to the neighboring areas. Saliency can also be used to detect heterogeneous regions to be highlighted in the rendered images (Itti, Koch, & Niebur, 1998; Kadir & Brady, 2001). Our proposed method enhances the visual representations of the dynamic and heterogeneous regions and reduces the rendering intensity of homogeneous and static regions based on a novel measurement of spatiotemporal saliency. However, this is a visual exploration rather than a

* Corresponding author at: Department of Geography and the Environment, University of Denver, Boettcher West, Room 120, 2050 E. Iliff Ave., Denver, CO 80208-0710, USA.
E-mail address: Jing.Li145@du.edu (J. Li).

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"push-button" approach, as users can control how the enhancements should be applied after examining the data distribution and through rendering experiments.

A brief description of the method is presented here. First, a multi-resolution data model is built using the time–space partition (TSP) tree to organize the original three-dimensional (3D) temporal data into data blocks. Saliency values are computed for each data block at different resolution levels. The saliency values are adjusted according to view angles to remove the occlusion effects and to highlight salient regions along the view directions. The adjusted saliency values are used to determine the regions to be rendered at higher or lower resolution levels, according to the threshold values selected by users. The color ramps assigned to those regions are adjusted to make salient regions more prominent. We implement the method within a remote visualization system that is deployed in a cloud environment. We have also conducted a set of experiments using datasets produced from a regional dust storm simulation model to evaluate the effectiveness of the proposed method.

The rest of the paper proceeds as follows: In Section 2, we review different categories of visualization enhancement methods, focusing on their applicability to interactive visualization of dynamic volumetric data. In Section 3, we describe the saliency-driven approach. In Section 4, we demonstrate the approach with results from our experiments. Conclusions and future directions are given in Section 5.

2. Visualization enhancement methods

Improving visualization efficiency and effectiveness is an important research topic in computer graphics and geovisualization. To achieve a reasonable interactive rendering speed, both hardware- (e.g., using multi-core graphics processing units (GPUs) to execute volume rendering; Li, Jiang, Yang, Huang, & Rice, 2013) and software-based solutions (e.g., levels of details (LODs); Li, Wu, Yang, Wong, & Xie, 2011) have been explored and developed. Software-based solutions adopt the general principle of using different visual variables (e.g., color, size, and orientation) to enhance graphical representations highlighting regions of interests (ROIs) (Dong, Ran, & Wang, 2012). Although several methods have been developed to either improve visualization efficiency *or* enhance visualization effectiveness, only a few address both objectives simultaneously (e.g., Wang, Wang, Lee, & Ma, 2011). In this section, we review only methods that address both objectives and analyze the applicability of these methods in the context of remote visualization for time-varying volumetric data.

2.1. Adaptive enhancement approach in computer graphics

Several methods have been proposed to improve the rendering efficiency and representation effectiveness. The typical approach includes three steps. The first step is to build a multilevel hierarchical data structure with each level consisting of aggregated data at a reduced spatial resolution. During interactive rendering, the lowest-resolution-level data are rendered whenever possible to improve the system efficiency. The second step is to highlight the ROIs according to the rendering criteria specified by users. An example is to render specific regions with high illumination colors and low transparency (Jankun-Kelly & Ma, 2001). Finally, the ROIs are represented at finer resolution levels, whereas less important regions are rendered at lower resolution levels. The visual enhancement achieved by this approach is the ROIs being shown with detailed information, whereas the rendering efficiency is achieved by reducing the rendering cost of the less important regions.

However, this visual enhancement approach does not consider the viewpoint location, which is a critical element in 3D visualization, as the ROIs may be occluded by other volumetric features (Bordoloi & Shen, 2005). Viola, Kanitsar, and Gröller (2005) proposed a method to identify occlusions based on viewpoint positions. This method assumes that the ROIs have been specified by users and regions occluding the ROIs (usually these are less important regions) are rendered at lower resolutions to allow the ROIs to be more discernable. Efficiency is also improved by rendering some features at a lower resolution.

Besides adjusting resolution, several methods highlight the ROIs by magnifying the ROIs with a simulated magnifying lens through the viewpoint (e.g., Wang, Zhao, Mueller, & Kaufman, 2005). The magnification reduces the overall rendering intensity by reducing the area with less important features, but it introduces intersections and distortions of the regions by showing the ROIs disproportionally larger. Recently, several methods have been developed to avoid intersections and reduce distortions (e.g., Wang et al., 2011). However, all these methods have at least two limitations when applied to remote visualization settings to handle time-varying volumetric data:

- All these methods are based on the graphical representations of original attribute values. Selecting different transfer functions to map attribute values to color ramps and opacities can change the identification results. Therefore, the correlation between data values and color values cannot be maintained when different functions are used. As a result, information captured by the original data may be interpreted inconsistently after rendering by different users if different functions are selected (Wang et al., 2011).
- To improve the computational efficiency for interactive rendering, rules used to identify ROIs are designed to be simple and computationally light at the expense of including areas that may not be part of the ROIs. Wang et al. (2011) suggest that the accuracy of identification has to be improved using more complicated methods, but these methods have not been efficiently implemented yet.

2.2. Cartographic optimization and enhancements

Adjusting the rendering resolutions based on local variations of data not only improves the visualization efficiency but also provides the optimal amount of information to users, as areas with little variation are rendered at lower resolution levels whereas areas with larger variations are rendered at higher resolution levels (e.g., Cecconi & Galanda, 2002). Local variations can also be highlighted further by enhanced graphical representations. Examples include methods used in terrain mapping. Indices evaluating surface roughness can be used to identify regions with prominent features, and illumination levels are adjusted according to the index values to enhance local contrast to highlight these features.

Unfortunately, these visual enhancement methods are not well suited for interactive remote visualization of time-varying volumetric data. Only a few approaches have been developed to enhance visual representations for 3D data (e.g., 3D terrain modeling, Podobnikar, 2012; 3D city mapping, Herman, Kýnová, Russnák, & Řezník, 2015). Unlike the rendering of static 2D or 3D data, visualizing 3D volumetric spatiotemporal data needs to consider viewing perspectives, viewing positions, and feature occlusions when designing enhancement methods. (e.g., Häberling, Bär, & Hurni, 2008). These factors are not considered in the existing methods (Resch, Hillen, Reimer, & Spitzer, 2013).

2.3. Saliency-driven methods

To visualize time-varying volumetric data efficiently and effectively in a remote visualization setting, we propose a saliency-driven method. Saliency refers to the concept of making the more important parts of a scene stand out so that they are more likely to attract users' attention. From the data perspective, salient regions are featured with rarity and high degrees of local complexity; therefore, they should be highlighted (Itti et al., 1998). Saliency-based visualization designs change the colors, opacity levels, or resolution of the selected regions to enhance their contrast to their neighbors (e.g. Kim & Varshney, 2006, Svakhine, Ebert, & Andrews, 2009). In addition to improving rendering effectiveness, the saliency concept has been used to simplify 3D models. To reduce