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Technical Section

Identifying nearly equally spaced isosurfaces for volumetric data sets☆

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ABSTRACT

Isosurfaces are an important visual representation of volumetric data sets and isosurface extraction and rendering remains one of the most popular methods for volume visualization. Previous works identify a small set of representative isosurfaces from a set of sample ones, providing a concise description of the underlying volume. However, these methods do not lend themselves to equally spaced isosurfaces, i.e., keeping the same distance between neighboring isosurfaces, which can be advantageous from the user's perspective in terms of visual summarization and interactive exploration. In this paper, we present a new solution that efficiently identifies a set of nearly equally spaced isosurfaces for a given volume data set. Our approach includes an estimation stage of linear interpolation and a refinement stage of binary search in order to balance the tradeoff between quality and performance. The refinement stage can incorporate spike and/or jump treatments to possibly improve the convergence. Experimenting with multiple data sets of different sizes and characteristics, we perform both quantitative and qualitative studies, demonstrate the efficiency and effectiveness of our approach, and summarize our findings.

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1. Introduction

Numerical simulations are extensively used by scientists to observe various phenomena that are not easily captured by real experiments. These simulations normally produce an ample amount of data, requiring effective tools to visualize and analyze them. A typical visualization presents the simulation results as a series of volumes. One of the essential techniques to gain insights into these volumes is isosurface rendering. To describe the structure of a volume, one can extract and visualize isosurfaces. These surfaces describe surface geometries with all points sharing the same isovalue. For insightful visualization, it is critical to select a set of salient isosurfaces that captures different features and characteristics of the underlying volume.

One common solution is to select a set of distinctive or representative isosurfaces from sample ones based on a certain similarity measure. For example, Tenginakai et al. [1] measured the similarities between isosurfaces using data histograms and higher order moments. Bruckner and Möller [2] derived distance fields from the sample isosurfaces and utilized mutual information to evaluate the similarity between the distance fields. The similarity values are organized in a matrix form named *isosurface similarity map* from which the representative isosurfaces are selected.

One major challenge exists for these approaches: it is essential for them to start with a set of reasonably good sample isosurfaces that capture different features in a balanced way. Otherwise, the features missing in the samples will not be recovered in the later stages, or the selection may be biased by favoring the features corresponding to more samples. However, straightforward sampling techniques do not guarantee the desired set of samples. Uniform sampling is likely to miss some features when many of them reside in a small value range. Although sampling according to histograms of voxel values, i.e., placing more samples in the value ranges with more voxels, may alleviate this problem to some degree, it still suffers from oversampling as the value ranges with more voxels do not necessarily indicate more distinctive features.

Another key challenge is posed by the scale and complexity of the data generated by numerical simulations. To obtain a comprehensive understanding of physical phenomena, the simulations usually involve multiple variables and their interactions over time, resulting in large-scale time-varying multivariate volume data sets. This requires a surface-based analysis to be efficient in two aspects. First, the distance between two isosurfaces should be measured efficiently. Second, the number of distance calculations should be minimized so that one can afford to take a full run and draw a complete picture of the data. Previous approaches focused more on the definitions of similarity measures and less on performance optimization. For example, it took around 25 min to process a single volume with the isosurface similarity map approach [2]. This cost becomes prohibitive when analyzing a typical time-varying multivariate data set with tens of variables and hundreds of time steps.

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In this paper, we present an approach for identifying nearly equally spaced isosurfaces, so that the distance between neighboring surfaces is as similar as possible to the average distance. In flow visualization, creating evenly spaced or mutually distant streamlines or stream surfaces has been well studied [3–5]. However, to the best of our knowledge, creating equally or evenly spaced isosurfaces has not been investigated. Our solution ensures that the isosurfaces corresponding to neighboring isovalues are distinct enough according to the given distance measure. When identifying a small number of isosurfaces, we can consider the resulting isosurfaces as salient features on their own. Compared to the similarity-based approaches for identifying representative isosurfaces, our approach does not require the isosurfaces to be selected from a limited set of sample ones. It not only has a wider search space but also explicitly controls over the resulting isosurfaces, which can potentially lead to better results. Compared to the topology-based approaches, our method is more flexible when equipped with different distance measures. Although this offers great flexibility, our method relies on features being a function of isovalues. Given that precondition, our algorithm may capture the topological changes if the distance measure is topology-aware, and it may produce isosurfaces with distinct shapes if the distance measure is shape-aware. In addition, when a large set of isosurfaces is identified, the results can serve as reliable input to other volume analysis and visualization tasks. In our experiment, we find that taking our results as the input, the representative isosurfaces selected using isosurface similarity map [2] and k-means [6] can be improved. The comparison results will be presented in Section 4.2.

Our approach includes two stages: an estimation stage that quickly converges to a rough solution within a few iterations, and a refinement stage that optimizes the estimation. For both stages, only the distances between neighboring isosurfaces are needed at each iteration. Leveraging the parallel computation of GPU, we can process each iteration efficiently. In addition, our approach can be flexibly customized with various distance measures to meet different needs. In our experiment, we compare the performance and sampling results using the isosurface similarity map (ISM) measure [2] and the mean of the closest point distances (MCP) [7].

The contributions of our work are as follows.

- First, we present a feasible solution to identifying nearly equally spaced isosurfaces, an important yet seldom investigated problem. We shall see that our solution does not fully converge in general but we are able to find a solution with acceptable quality and performance tradeoff. Compared to similarity- or topology-based methods, the set of isosurfaces generated by our method provides an advantageous visual summarization of the volumetric data, especially when the number of surfaces is small.
- Second, we perform a thorough study to compare parameter choices, distance measures, and qualitative results, followed by a list of findings for other researchers to follow. The proposed solution can be adopted by others for incorporation into their high-performance volume data analysis and visualization workflow.

2. Related work

To analyze and visualize volumetric data sets, researchers have sought different kinds of methods to understand the structures of volumes. The *distribution-based* methods focus on the distributions of certain properties of the volume and identify the salient structure based on their corresponding statistical characteristics. The *topology-based* methods analyze the topological structure of the volumes and highlight the structures corresponding to topological changes. The *similarity-based* methods measure the similarity between volume representations such as isosurfaces and derive the representative ones based on their similarities.

2.1. Distribution-based methods

Understanding the relationships between the volume distribution and the isosurfaces allows us to identify salient features. For instance, Tenginakai et al. [1] detected salient isosurfaces using local higher order moments (LHOMs). LHOMs are computed and plotted for different sample values for a semi-automatic selection. Scheidegger et al. [8] applied Federer's Coarea Formula to improve the isosurface statistics by weighting with the inverse gradient magnitude. Duffy et al. [9] developed a mathematical model for continuous functions and proved the convergence to continuous statistics for regular lattices. Pekar et al. [10] proposed to use Laplacian weighted histograms for significant isovalue detection. However, the distribution of a volume data set does not translate to the spatial relationship among surfaces extracted, which is the focus of this paper.

2.2. Topology-based methods

These methods extract structures that essentially characterize properties of space such as convergence, connectedness, and continuity, providing a concise description of the overall structure of a volume. Bajaj et al. [11] proposed the contour spectrum, an interface combining the contour tree together with a variety of isosurface statistics, such as area and enclosed volume. Bremer et al. [12] presented the cancellation tree for describing the simplification of a Morse–Smale complex. Each simplification step cancels a pair of critical points, i.e., minima and maxima. The cancellation tree encodes the simplification steps and provides the connections among critical points. They further extended this approach to the hierarchical merge tree, which is a tracking graph that describes the temporal evolution of features [13]. Carr et al. [14] proposed to use the contour tree to encode the nesting relationships among isosurfaces. It also serves as an interface that allows users to select contours for operations such as removal, evolution, and tracking. Correa et al. [15] introduced the topological spine that connects critical points along the steepest ascending or descending directions. In addition, it includes geometric and contour nesting information, providing better spatial reasoning.

Although rigorous, topology-based methods normally capture minute topological changes, which lead to a large number of isourfaces for a volume with complex topological variations. This, however, may not always be necessary for users to understand the overall structure of the volume. In contrast, our approach generates a small set of nearly equally spaced isosurfaces which are more amenable for user observation: each surface is distinct enough and they are mutually distant in the space. Such a set of isosurfaces could also be useful as a visual summarization of the underlying volume.

2.3. Similarity-based methods

Recent works often seek to measure the similarities between a set of sample isosurfaces and derive the structure of the entire volume. For example, Bruckner and Möller [2] evaluated the similarity between isosurfaces and organized them in the form of an isosurface similarity map. The similarity between two isosurfaces is defined as the mutual information shared by the distance fields of the two isosurfaces. Representative isosurfaces are identified using the isosurface similarity map, which stores all pairwise similarity values. Haidacher et al. [16] extended this approach to compare isosurfaces extracted from multiple volumes. Wei et al. [17] proposed a similarity measure between two isosurfaces based

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