Feature-Driven Volume Fairing

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Abstract. Volume datasets have been a primary representation for scientific visualization with the advent of rendering algorithms such as marching cubes and ray casting. Nonetheless, illuminating the underlying spatial structures still requires careful adjustment of visualization parameters each time when a different dataset is provided. This paper introduces a new framework, called feature-driven volume fairing, which transforms any 3D scalar field into a canonical form to be used as communication media of scientific volume data. The transformation is accomplished by first modulating the topological structure of the volume so that the associated isosurfaces never incur internal voids, and then geometrically elongating the significant feature regions over the range of scalar field values. This framework allows us to elucidate spatial structures in the volume instantly using a predefined set of visualization parameters, and further enables data compression of the volume with a smaller number of quantization levels for efficient data transmission.

1 Introduction

Volume datasets have become a primary representation of scientific data with the advent of visualization algorithms such as marching cubes and ray casting. Nonetheless, even with any visualization strategies, illuminating spatial structures inherent in such datasets clearly needs careful adjustment of visualization parameters. For example, transfer function design has intensively been studied in the computer visualization community since the late 1990's [1], while we still need to prepare different sets of visualization parameters when new datasets are provided.

This paper introduces a novel framework, called *feature-driven volume fairing*, which transforms any 3D scalar field into a canonical form to be used as communication media of scientific volume data. The transformation is accomplished by modulating arrangement of features in the volume, and thus allows us to easily visualize the modulated data with a set of naive visualization parameters. The key tool to our approach is the contour tree that enables systematic transformation of the given scalar field by accounting for the topological evolution of isosurfaces. The actual fairing process consists of three modulation steps; topological modulation, geometrical modulation, and smoothing modulation. The topological modulation transforms the given volume data so that the associated isosurfaces never incur internal voids as the scalar field value decreases. This is useful because we can intentionally discriminate such internal voids from their

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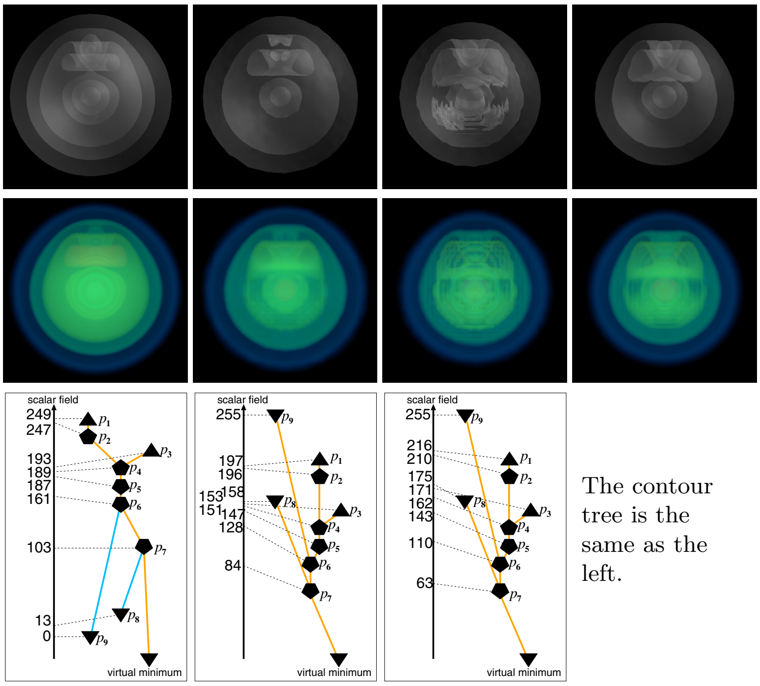


(a) (b) (c) (d)

Fig. 1. Effects of volume fairing process for the nucleon dataset (of resolution 41^3) (http://www.volvis.org/). (a) An original volume dataset. (b) The dataset after topological modulation. (c) The dataset after geometrical modulation. (d) The dataset after smoothing modulation. Isosurfaces at uniformly spaced scalar field values (top), rendered image with periodical accentuated opacity transfer function (middle), and the corresponding contour trees while edges of internal voids are drawn in blue (bottom).

exterior layers in the rendering process after this modulation step. On the other hand, the geometrical modulation accentuates significant regions while suppressing the remaining regions, by rearranging their corresponding scalar field values to be spaced rather uniformly over their entire range. Finally, the modulated scalar field is smoothed out spatially by solving the Poisson equation based on the discrete differences between a pair of neighboring voxels. This threefold modulation process also allows us to compress the size of the datasets for efficient data transmission, just by cutting out a few lower quantization bits of all the bits for the entire range of scalar field values.

Fig. 1 presents the effects of our feature-driven fairing process for the nucleon volume dataset, where the two-body distribution probability of a nucleon in the atomic nucleus ^{16}O is simulated. We can notice from the figure that the modulated volume (Fig. 1(d)) can systematically reveal its unique internal structures while we are likely to miss them in the original dataset since the internal structures are occluded by multiple exterior isosurfaces (Fig. 1(a)).

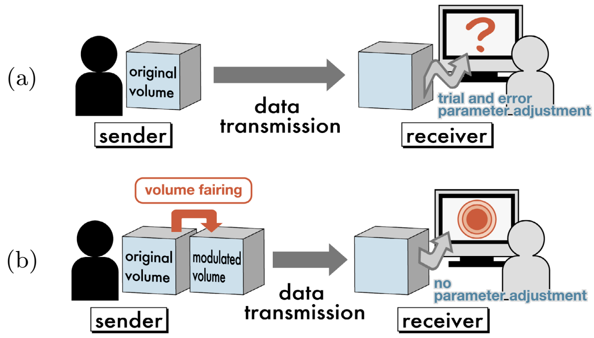


Fig. 2. Schemes for transmitting scientific volume datasets. (a) The existing scheme. (b) Our new scheme.

Unlike the existing volume rendering scheme (Fig. 2(a)), once the sender/generator has successfully transformed the given volume dataset to its canonical form using the volume fairing technique, the receiver/user can instantly elucidate its associated features with a set of predefined visualization parameters (Fig. 2(b)). Providing effective data representation for this communication model is the primary issue to be tackled in this study.

This paper is organized as follows: Section 2 provides a brief survey on researches related to this work. Section 3 describes an algorithm for transforming the given volume dataset to its canonical form by modulating the arrangement of features over the range of scalar field values. Section 4 presents several experimental results together with an application to the data compression. Section 5 concludes this paper and refers to possible future developments of this work.

2 Related Work

Our research can be thought of as an attempt to leverage topological filtering for advancing *collaborative* volume exploration in *distributed* environments.

Facilitating collaborative volume exploration requires an effective way to share among colleagues, feature structures acquired from target volume datasets. An extreme case for this purpose is just to exchange resultant visualization images, at the sacrifice of progressive exploration style. Geometry fitting and arbitrary slicing have also been commonly used to provide an efficient interface for mutual understanding of explicitly-extracted features. Many reports on topological enhancements can be found in the literature, including topologically-enhanced isosurfacing [2], solid fitting [3], and cross-sectioning [4].

However, to avoid excess cutout of information at the sender side, and to expect further findings through the “first personal examination” at the receiver side, volumes themselves still serve as most meaningful communication media. Representative accompanying communication media used so far are transfer functions [1], which can convey the acquired volumetric features implicitly in the form of color and opacity. Topological analysis has been used mostly in the context of transfer function design [5,6], whose merit lies in that the designed transfer functions can delineate global structures in the volume as well as its local features, thereby making good contrast with other transfer function design methods that only allow for local features such as curvature [7].

3 Feature-Based Volume Modulation

This section presents an algorithm for transforming a given volume dataset to its canonical form to provide a standard communication media for scientific data. As described earlier, the volume fairing consists of three stages: topological modulation, geometrical modulation, and smoothing modulation. In the remainder of this section, requirements for our approach are first described in Section 3.1 and then the details of the algorithm are provided through Sections 3.2-3.4.

3.1 Requirements

Here, we strive to summarize the list of requirements for the canonical representation of volume datasets in our framework. Our initial intention is to develop a standard representation of scientific volume datasets for elucidating significant features with a set of naive visualization parameters, even when the accompanying features are imperceptibly embedded in the 3D volumes. This means that, once a sender/generator successfully transforms the scientific volume data in such a way, a receiver/user significantly reduces his or her amount of user interaction for adjusting the visualization parameters. This will be the ideal communication scheme for exchanging scientific data we are going to pursue in this study.

In the present framework, the predefined setting of visualization parameters is assumed to be a set of scalar field values uniformly sampled over the entire range when extracting isosurfaces using the marching cubes algorithm, and periodically accentuated opacity and uniformly changed color transfer functions when rendering using the ray casting technique. This motivates us to elongate the regions of interest over the range of scalar field values, so that we can identify significant features even with the uniform sampling of the scalar field range.

The above transformation, which is referred to as *geometrical modulation* in this paper, can optimize the distribution of feature regions over the entire range of scalar field values. However, it cannot separate isosurfaces that compose a multi-layered structure. This case incurs undesirable results in the above framework since we cannot accentuate the internal features while suppressing their exteriors using naive one-dimensional transfer functions. For making full use of such naive transfer functions, our algorithm intentionally decomposes such a nested structure into distinct exterior and interior isosurfaces. This modulation, called *topological modulation* in this paper, rearranges the spatial structures in the volume dataset by successfully eliminating the multi-layered isosurface structure while maintaining the global isosurface evolution. Nonetheless, these processes cannot necessarily maintain the spatial smoothness in the volume data.

We alleviate this problem by postponing a smoothing modulation stage by taking advantage of the optimization process based on the Poisson equation.

This threefold modulation process will allow receivers/users to easily highlight significant features of a given dataset only with a set of naive visualization parameters, irrespective of what the sender/generator did in the volume faring process beforehand. An outgrowth of this fairing process is the ability to reduce the data size by simply cutting out a few lower quantization bits of all the bits for the entire dynamic range of scalar field values. This consequently enables efficient data transmission through the network.

3.2 Topological Modulation

The topological modulation transforms the topological transitions of isosurfaces in order to eliminate inclusion relationships among significant isosurfaces at any scalar field value. For that purpose, we introduce a contour tree representation [2,8] since it faithfully represents such topological transition of isosurfaces. Fig. 3(a) represents an example of such a contour tree representation while the positions of the associated nodes, which correspond to topological changes in the isosurfaces, are arranged from top to bottom as the corresponding scalar field value decreases. Actually, the topological modulation is equivalent to converting each downward branch of the contour tree in Fig. 3(a) (in blue) to an upward branch (in orange) as shown in Fig. 3(b). This is fully justified because the downward branches inevitably introduce internal voids into some exterior isosurfaces by taking account of their spatial embeddings into 3D space [3,6]. In addition, this rearranged contour tree allows us to peel the given volume from outside to inside by tracking the tree from bottom to top. For example, as shown in Fig. 3, the internal void outlined in red has successfully been transformed to the solid part.

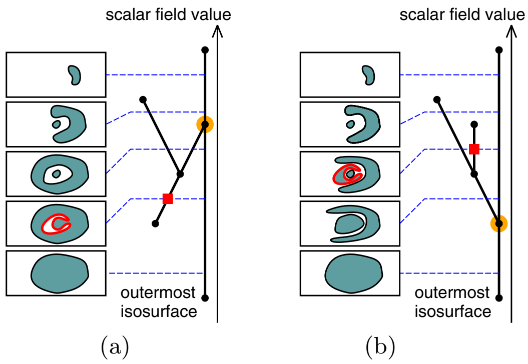


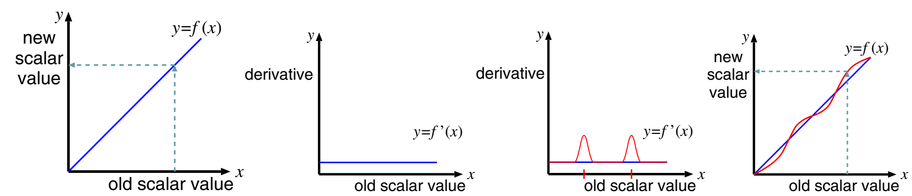
Fig. 3. Contour trees (a) before and (b) after topological modulation: (a) A downward branch represents the topological transition where some isosurface is about to have internal voids. (b) By converting the downward edges (in blue) to upward ones (in orange), we can eliminate the multi-layered isosurface structure.

The actual conversion process of the contour tree begins with identifying the extremal node that corresponds to the outermost isosurface of the given volume (Fig. 3(a)). We then traverse the tree using this extremal node as a starting point, and update the height coordinate of each intermediate node with its geodesic distance from the starting node on the contour tree. This coordinate transformation along with an appropriate normalization of the height range will provide us with the final topologically modulated contour tree (Fig. 3(b)). Note that we employ the algorithm in [5] for extracting the simplified version of the contour trees, in order to delineate the global topological transitions of isosurfaces embedded in the given volume data. Fig. 1(b) represents the nucleon dataset and its contour tree after the topological modulation process.

3.3 Geometrical Modulation

The next task is to conduct the geometrical modulation, which elongates the feature regions while preserving their relative order over the range of scalar field values. This makes it possible to retrieve the important configuration of isosurfaces by rather sparsely sampling the range of scalar field values. For finding well-balanced distribution of such features over the range, we first suppose a function $y = f(x)$ that maps the current scalar field value x to its modulated value y. The geometrical modulation begins with the preparation of an initial linear mapping between x and y (Fig. 4(a)), and its associated constant derivative (Fig. 4(b)). The derivative is then accentuated around some specific feature values by adding Gaussian-like kernel distributions accordingly (Fig. 4(c)). The final mapping $y = f(x)$ between the original and modulated scalar field values is obtained by integrating the above accentuated derivatives, followed by the normalization of the modulated dynamic range of the scalar field values (Fig. 4(d)).

In our framework, saddle critical values comprising isosurface splitting and merging are used as feature values (in red in Fig. 4(c)) to be accentuated in the volume fairing process. This is reasonable because we can illuminate the spatial configuration of feature isosurfaces easily with the predefined setting of



(a) (b) (c) (d)

Fig. 4. Geometrical modulation. (a) An initial linear mapping between the old and new scalar field values. (b) Its constant derivative. (c) The accentuated derivative by adding Gaussian-like kernel function around the feature values (in red). (d) The final feature-driven modulation of scalar field values.

Table 1. Computation times (in seconds)

Dataset	Size	Topological	Geometrical	Smoothing	Total
Nucleon	41^3	5.06	0.01	0.18	5.24
Analytic function	33^3	1.01	0.01	0.09	1.11
Proton & hydrogen-atom	61^3	1.99	0.02	1.32	3.33
Anti-proton & hydrogen-atom	129^3	17.29	0.17	144.84	162.30

visualization parameters. Fig. 1(c) represents the contour tree and its associated visualization results after the geometrical modulation.

3.4 Smoothing Modulation

Basically, the volume fairing process has been done by modulating the associated contour tree as described above, and then the scalar field value of each voxel is changed accordingly by referring to the corresponding node on the modulated contour tree. Nonetheless, only with this modulation, the resultant 3D scalar field is not necessarily smooth enough, and thus contains unexpected artifacts as shown in Fig. 1(c). For removing such artifacts, we postponed an optimization process based on the Poisson equation. Such optimization processes have been introduced in the high dynamic range data compression [9], and further applied to the compression of depth information such as the range image data compression [10,11]. The present approach, on the other hand, tries to develop a method of smoothing out the input 3D scalar field while referring to the modulated contour tree as guidelines for the coherent fairing.

The actual reconstruction of the 3D scalar field is accomplished by integrating the given gradients while minimizing the associated integration errors. Solving the following Poisson equation allows us to obtain the optimized 3D field of scalar values $f(x, y, z)$:

$$\nabla^2 f = div\,\mathbf{g}, \quad \text{where} \quad \mathbf{g} = \nabla f = (\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}). \tag{1}$$

Here, each of the partial derivatives can be obtained by calculating the discrete central difference in the corresponding scalar field value. Note that, for solving the Poisson equation in (1), we introduce a Neumann boundary condition to the outermost voxels of the given dataset. By solving the Poisson equation, we can reconstruct the smooth 3D scalar field, as shown in Fig. 1(d).

4 Results

This section provides several experimental results to demonstrate the effectiveness of the present framework. Note that all the given volume datasets are assumed to have an 8-bit quantization representation (256 discrete levels) of the scalar field values. Our prototype system has been implemented on a laptop PC

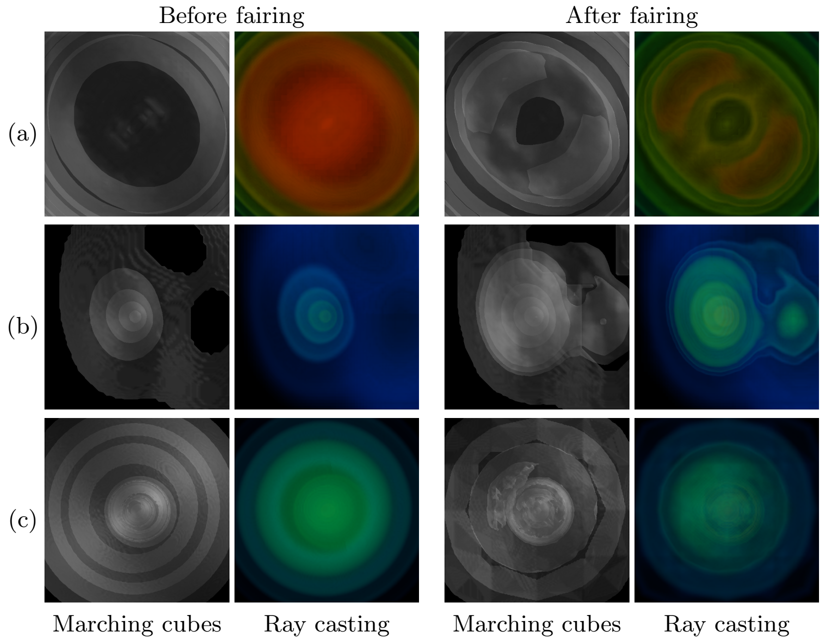


Fig. 5. (a) Analytic function dataset (of resolution 33^3), (b) proton and hydrogen-atom collision dataset (of resolution 61^3), and (c) anti-proton and hydrogen-atom collision dataset (of resolution 129^3), before and after the volume fairing process. Isosurfaces at uniformly spaced scalar field values (left), and rendered image with periodical opacity transfer function (right) in each column.

with Intel Core2Duo T9500 CPUs running at 2.60GHz and 4GB RAM. Table 1 summarizes the computation times required for each of the three modulation processes on the above computational environment.

4.1 Visualizing Modulated Datasets

Let us examine how the present volume fairing scheme will alleviate the need to adjust the visualization parameters. For each case, we applied the marching cubes algorithm for isosurface extraction, and the ray casting algorithm for illuminating internal structures. For extracting isosurfaces, we uniformly sample the entire range of scalar field values to reveal isosurface transition. For illuminating the spatial structures with cast rays, we employ an opacity transfer function where hat-like elevations are placed at even intervals over the entire range of the scalar field values. Note that the color transfer function is set to be a naive one where the hue is uniformly changed over the scalar field range.

Furthermore, for each rendering process, we put more emphasis on voxels having larger scalar field values because, in our setting, interior feature regions have larger scalar field values than the exterior regions. For example, we assign more alpha values to isosurfaces at larger scalar field values, and we augment

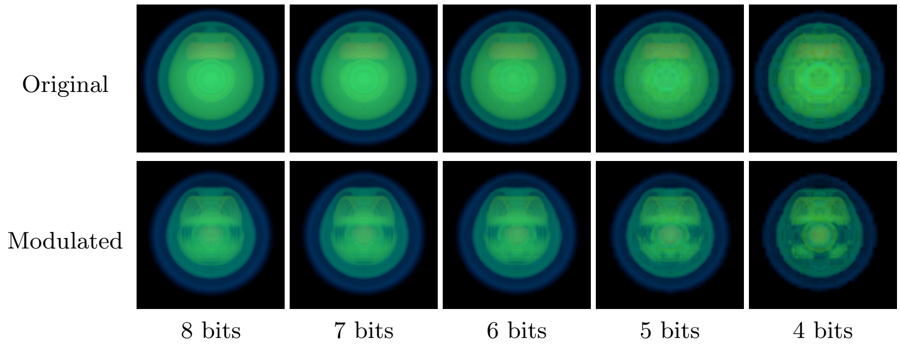


Fig. 6. Compression of the nucleon dataset by cutting off lower quantization bits. The original dataset (top) and the modulated dataset (bottom).

the height of the hat-like elevation in the opacity transfer function as the scalar field value increases.

Fig. 5 presents visualization results of the analytic function (Fig. 5(a)), proton and hydrogen-atom collision (Fig. 5(b)), and anti-proton and hydrogen-atom collision datasets (Fig. 5(c)), before and after the volume fairing process was conducted. The modulated datasets can exhibit clear views of the configuration of feature isosurfaces while the original dataset often fails to illuminate important features in the associated rendering results. Note that the anti-proton and hydrogen-atom collision dataset contains a fourfold nested structure of isosurfaces, which has not been appropriately visualized so far without the use of more visualization parameters for multi-dimensional transfer functions.

4.2 Data Compression

Our volume faring process provides a well-balanced distribution of scalar field values, and thus the resultant canonical dataset can readily be compressed by simply cutting out lower quantization bits for the scalar field values, while still maintaining the global features embedded in the original dataset. Fig. 6 represents the rendered image obtained from the original and compressed nucleon dataset through the aforementioned setting of transfer functions. The figure indicates that the important nested structure in the original dataset has been obscured when the number of quantization bits is reduced to 4, while the modulated dataset still retains a clear view of such features in a reasonable manner.

5 Conclusion and Future Work

This paper has presented a new framework, called feature-driven volume fairing, which allows us to illuminate the underlying features in the scientific volume datasets with naive visualization parameters once the datasets have been appropriately transformed to their canonical forms. The transformation has been accomplished by modulating the topological structure of the given volume first, then by elongating scalar field ranges containing significant features, and finally by smoothing the spatial distribution of scalar field values. Several experimental results suggest that the present methodology has the potential to serve as an efficient communication model of the scientific data through the network.

One interesting extension of this work is to accommodate more complicated datasets such as multivariate and time-varying volumes. Smoothing non-grid voxel samples with the Poisson equations should be handled. More sophistication of the system interface also remains to be investigated. The implementation of a more systematic data transmission together with the capability of demand-driven data queries poses another potential extension of the present framework.

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