Introducing Topological Attributes for Objective-Based Visualization

Yuriko Takeshima
JAERI

Shigeo Takahashi
Univ. of Tokyo

Issei Fujishiro
Ochanomizu Univ.

Gregory M. Nielson
Arizona State Univ.

1 Introduction

Direct volume rendering is a standard technique for projecting all the optically-encoded samples onto the screen at once to allow us to peer into the inner structures involved in a volume data. Data-centric approaches to the design of *transfer functions* (*TFs*) have recently been well-established, which perform mathematical analysis of the data prior to pertinent rendering. The advent of *multi-dimensional* TFs is one of the latest major achievements in the volume visualization research. As opposed to the traditional one-dimensional TFs that only consider a voxel's scalar field value, the multi-dimensional TFs assign auxiliary attributes to the voxels to construct their sophisticated parametric domains. For example, when visualizing volumes obtained by scientific simulations, the observers can utilize their own knowledge about the simulation settings to extract the global characteristics of the volumes and to locate regions of particular interest. If they are allowed to design multi-dimensional TFs using staff attributes so as to encapsulate such advance knowledge, they can readily yield visualization results to fulfill their purposes. Nevertheless, nearly all attributes for the conventional multi-dimensional TFs are based on local features, such as differentials and curvatures, and are difficult to capture the global structure of the volume contrary to the observer's purposes.

This paper therefore introduces a new set of topological attributes to establish a new framework that is intended to realize objective-based assistance. Topological attributes proposed herein are derived from the level-set graph, which delineates the topological evolution of an isosurface with respect to the scalar field.

2 Topological Volumetric Skeletonization

We assume that a volume dataset is represented by sample points of a single-valued function. Cutting a volume dataset at different scalar field values will produce topological changes of isosurfaces, including isosurface splitting and merging. We represent such isosurface transition using a level-set graph, called volume skeleton tree (VST)[1] that delineates such global isosurface trajectories passing through their local topological transitions.

The node of the VST represents *critical point* that has the change either in the number of isosurface connected components or in the genus of each of the isosurface components. They are classified into four groups: maxima (C_3), saddles (C_2), saddles (C_1), and minima (C_0), which represent isosurface appearance, merging, splitting, and disappearance, respectively, as the scalar field value reduces. The link of the VST represents an isosurface component which is defined *solid* if it expands as the scalar field value reduces while *hollow* if it shrinks. The isosurface merging at C_2 and splitting at C_1 have both four topological transition paths with different isosurface spatial configurations as shown in Fig. 1. In what follows, VST uses the notation for the critical points with its own connectivity as illustrated in Fig. 1, where the orange incident link represents a solid isosurface while the blue link represents hollow. For later convenience, all the boundary voxels are assumed to be connected to the virtual minimum having $-\infty$ as its scalar field value [1]. Note that the link incident to a C_0 node is solid when the node is the virtual minimum as shown in Fig. 1. In our implementation, the node has its coordinates and scalar field value, and the link has its genus and index of adjacent nodes.

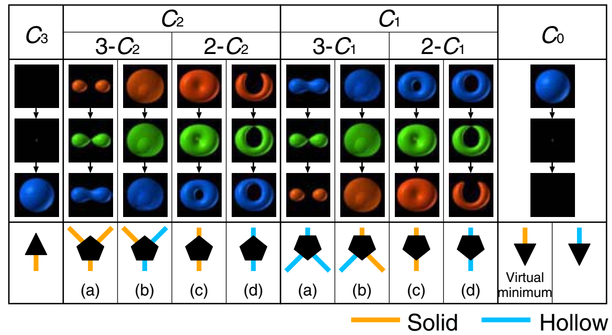


Figure 1: The connectivity of a critical point of each type in the VST: The orange and blue lines represent the links that correspond to solid and hollow isosurfaces, respectively.

3 Designing Multi-Dimensional Transfer Functions with Topological Attributes

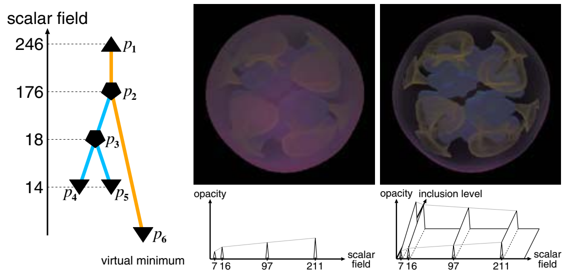
In this section, we illustrate that adaptive usage of topological attributes, which are formulated using the VST, makes it possible to obtain visualization results emphasizing various structures of volumes through effective usage of multi-dimensinal TFs.

(1) Inclusion level

A volume dataset often includes a complicated nested structure where one feature subvolume completely encloses others within some range of the scalar field value. Here, the inclusion level of a voxel represents the depth of its associated isosurface in the nested structure at the corresponding scalar field value. It is clear from Fig. 1 that isosurface nested structures originate only from the transition paths in C_2(b) and C_3(b). This suggests that we can locate such isosurface inclusions directly from the VST if we can identify the nodes C_2(b) and C_1(b).

Fig. 2 visualizes a snapshot volume for 3D fuel density distribution simulating the process of implosion in laser fusion [2], where small bubble-spike structures evolve around a contact surface between a fuel ball (inner) and pusher (outer) during the stagnation phase. The fuel-pusher contact surface can be identified with an isosurface extracted by observing the rapid gradients of the fuel density field, whereas the extracted isosurface has two nested connected components, and the contact surface of our interest is occluded by the other outer component residing in the pusher domain, which is a phantom surface induced by the action-reaction effect.

Fig. 2(a) shows the VST for the implosion dataset, where the skeletal structure of the complex fuel density distribution has been extracted with an intentional control of VST simplification. A glance at the VST around the scalar field interval $[14, 176]$ finds a nested structure where connected isosurface components corresponding to the links $\overline{P_2P_3}$, $\overline{P_3P_4}$, and $\overline{P_3P_5}$ are included by another connected isosurface component corresponding to the link $\overline{P_2P_6}$. A volume-rendered image is shown with the topologically-accentuated 1D opacity TF in Fig. 2(b), from which we can see that after the scalar field itself has been topologically-accentuated, we still suffer from a problem that the inner isosurface components of interest for the observer are indeed occluded by the outer spherical isosurface component. Contrary to that, as shown in Fig. 2(c), if we



(a) (b) (c)

Figure 2: Visualizing simulated implosion in laser fusion: (a) The corresponding VST, (b) topologically-accentuated 1D opacity TF, (c) 2D opacity TF depending also on the inclusion level.

devise the 2D opacity TF which depends on the inclusion level as well to assign a lower opacity value to voxels on the outer isosurface component than to voxels on the inner ones, we can observe the optically-deeper bubble-spike structures more clearly than in Fig. 2(b).

(2) Isosurface-trajectory distances

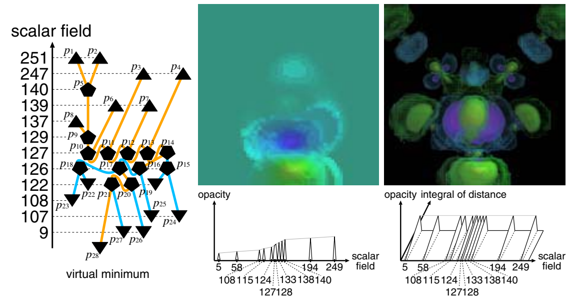
Simulated volume datasets such as distributions of energy functions often contain a symmetric isosurface trajectory with respect to the mean scalar field value. Such datasets involve an isosurface transition where the outermost isosurface component gradually expands and occupies the whole volume domain when the scalar field reaches a center value of symmetry. In our framework, *isosurface-trajectory distance* is defined as the difference in the scalar field between any two points along the shortest path on the VST. Using the integral of this quantity, we can identify the center of the its VST as the isosurface component that hides the inner structures of the volume.

For example, as shown in Fig. 3, the High Potential Iron Protein (HIPIP) dataset has a symmetric wave function with respect to the mean scalar field value, and thus the isosurface component around the mean value covers up the entire volume. Fig. 3(a) shows the VST of the HIPIP dataset, and Fig. 3(b) shows a visualization result obtained using topologically-accentuated 1D opacity TFs. As seen in Fig. 3(a), the VST is almost symmetric and it has many critical points around the mean scalar field value 127. However, the corresponding isosurface component actually occludes many significant features as shown in Fig. 3(b) if we assign a large opacity value to voxels associated with the occluding isosurface component. This observation motivates us to improve the result, as shown in Fig. 3(c), by lowering the opacity values of the voxels that have the small integral values of the distance in exchange of equalizing all the accentuation levels at the largest integral value. Indeed, this allows us to eliminate the occluding isosurface component from the important structures inside the volume.

(3) Isosurface genus

The change in genus of each component of an isosurface may provide an important clue which allows us to visually understand the complexity of the structures embedded in a volume dataset. *An isosurface genus* is equivalent to the number of holes on each of the isosurface connected components. Actually, the change in this number often outlines some distinctive feature subvolume embedded in the given dataset. This attribute is already accessible from VST.

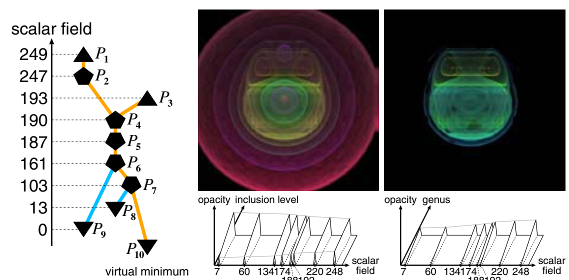
For example, Fig. 4 visualizes the half domain of positive charge distribution simulated around two ^{16}O nucleons. From the VST shown in Fig. 4(a), we can see that two isosurface components corresponding to the links $\overline{P_6P_9}$ and $\overline{P_7P_8}$ are included by the outer isosurface component. Fig. 4(b) shows a visualization result rendered with an accentuated 2D TF based on its nested structure. This



(a) (b) (c)

Figure 3: Visualizing the HIPIP dataset: (a) The corresponding VST, (b) topologically-accentuated 1D opacity TF, and (c) 2D opacity TF depending also on the integral of the isosurface-trajectory distance.

resultant image certainly provides useful information for us to understand the nested structure, though the image cannot be said to provide sufficient information for us to realize the complex interaction between the two nucleons. A resultant image rendered with a new 2D TF is shown in Fig. 4(c), where voxels which belong to isosurface components of genus 1 corresponding to the links $\overline{P_2P_4}$ and $\overline{P_4P_5}$ are emphasized. In fact, the region topologically equivalent to a torus coincides with the subspace having complex interactions between the two nucleons, and attracts much attention from the observers. Furthermore, the visualization result pinpoints the locations where the change in genus is invoked, and provides the observers with important visual cues about the detailed spatial configuration of each of the ^{16}O nucleons.



(a) (b) (c)

Figure 4: Visualizing the ^{16}O nucleon dataset: (a) The corresponding VST, (b) 2D opacity TF depending also on the inclusion level, and (c) 2D opacity TF depending also on the isosurface genus.

4 Conclusion

In this paper, we proposed a set of topological attributes derived from level-set graphs, and presented the basic design principles of multi-dimensional TFs depending on these attributes.

Remaining issues for our future research include enriching the set of topological attributes towards more powerful analysis, and identifying the mutual relationships between the topological attributes and the traditional local features such as gradients and curvatures for realizing more advanced visualization operations.

References

[1] TAKAHASHI, S., TAKESHIMA, Y., AND FUJISHIRO, I. 2004. Topological volume skeletonization and its application to transfer function design. *Graphical Models 66*, 1, 24–49.

[2] SAKAGAMI, H., MURAI, H., SEO, Y., AND YOKOKAWA, M. 2002. 14.9 TFLOPS three-dimensional fluid simulation for fusion science with HPF on the Earth Simulator. In *Proc. Supercomputing 2002*.