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MULTISENSORY REALIZATION USING TOPOLOGY-ACCENTUATED VISUALIZATION

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ABSTRACT

Computer visualization is widely used to analyze various phenomena in many areas. It is useful to explore the target dataset which has a few physical fields, but it is hard to understand multiple fields simultaneously. Especially, in flow fields, since most datasets have vector field and its associated multiple scalar fields, we are faced with the above problem as long as we rely only on visualization. In this paper, we focus on a multisensory realization method that combines haptization with visualization for the analysis of flow fields. We propose the use of adaptive visual transfer functions which are based on the topological structure of a target scalar field. Haptic transfer functions, which produce three-dimensional forces, are designed to analyze the vector field in a haptic manner. We evaluate the effectiveness of our method using a time-varying three-dimensional wake turbulence dataset.

1. INTRODUCTION

In general, numerical simulation datasets have multiple physical field values, such as temperature, pressure, velocity, and vorticity. Computer visualization is widely used as a powerful tool to reveal important mutual dependency of such numerical values in the target dataset. However, human visual cognition does not have sufficient capabilities to simultaneously discern a lot of information that are represented by shapes with their colors and opacities. For this reason, visualization has its own limitation when analyzing multiple physical fields simultaneously. Especially, since fluid datasets have vector field and its associated multiple scalar fields, we are faced with the problem as long as we rely only on visual analysis. In this paper, we therefore propose a topology-based multisensory realization method that combines haptization with visualization for such flow fields. Realization refers to a technique that represents a target object using virtual reality technologies [1]. The accuracy of haptization is not too high to recognize precise numerical values. However, it can be used to identify the strength and direction effectively. As our previous studies, we proposed realization methods for two-dimensional flow fields [2] and three-dimensional flow fields [3]. However, both of these methods considers only scalar fields and do not handle vector fields.

Figure 1 shows the processing flow of our method. In our approach, differential topology analysis [4] is used initially to identify the topological structure of a target scalar field. Next, visual transfer functions are designed based on the obtained topological structure. We also create haptic transfer functions with three degrees-of-freedoms (DOFs) to produce three-dimensional forces, which enable the identification of the vector field in real time.

We evaluate our method using a wake turbulence dataset. Wake turbulence is formed behind a moving aircraft, and it may be hazardous during takeoff and landing [5]. Wingtip vortices are the most dangerous components of wake turbulence, and they may persist in the air for several minutes after takeoff; thus, the next aircraft is required to wait for a fixed period before receiving takeoff clearance. To avoid serious accidents, wake turbulence dynamics should be analyzed in greater detail through simulation and realization.

2. TOPOLOGICAL ANALYSIS

In order to detect the critical points when there occur changes in the structure, we extract the topological structure of a given scalar volume dataset using the topological volume skeletonization algorithm [6]. The volumetric skeleton tree (VST) [4] allows us to evaluate the topological structure by considering both the global and local features of the scalar volume.

A node of the VST represents a critical point where a change occurs either in the number of connected isosurface components or the genus of each of the isosurface components. The three-dimensional critical points are classified into four groups: maxima (C_3), saddles (C_2, C_1), and minima (C_0), which represent the isosurface appearance, merging, splitting, and disappearance, respectively, as the scalar field value decreases. The index of a critical point, which is used as the suffix of its type, represents the number of negative eigenvalues in the Hessian. A link in the VST represents a topology-preserving transition of a connected isosurface component.

The isosurface that merges at C_2 and split at C_1 has both four topological transition paths with different isosurface spatial configurations, as shown in Fig. 2. In the following, the VST uses notations for the critical points based on

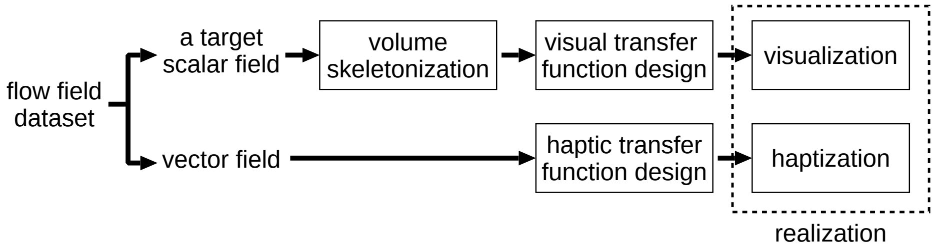


Figure 1: A processing flow of our method

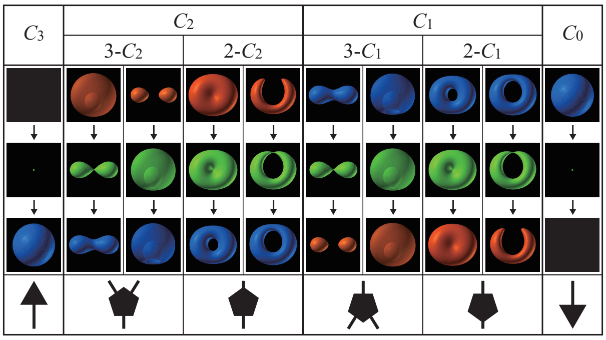


Figure 2: Connectivity of critical points in volumetric skeleton tree.

its connectivity, as shown in Fig. 2. The saddle points of $C_i(i = 1, 2)$ are classified as 3-C_i and 2-C_i, according to their degree. For convenience, all the boundary voxels are assumed to be connected to the virtual minimum, which has $-\infty$ as its scalar field value [4]. In our implementation, a node has coordinates and a scalar field value, while a link has its genus and an index of adjacent nodes. Also, we aim to reduce the complexity of the extracted VST until it is sufficiently simple to express the underlying global structure of the volume. The simplification of the VST is achieved by assigning a weight value to each link of the VST and eliminating the link with the smallest weight value one by one.

3. REALIZATION METHOD

To comprehend the behavior of flow field in a more intuitive manner, we need to design appropriate visual and haptic transfer functions.

3.1. Visual Transfer Functions

We use the topology-accentuated volume rendering [7] to reveal the inner structure of the scalar field in a target dataset.

In general, users determine the distributions of field values by using the color hues as indicators in the visualized images. However, if the color hue transfer function changes during at each time step, the users may be confused about the specific color hue that is assigned to each field value. Thus, we use a constant color hue transfer function, which assigns hues in a linear manner from the minimum field value to the maximum field value of the target time-series dataset, for all of the snapshots in the remaining part of this paper.

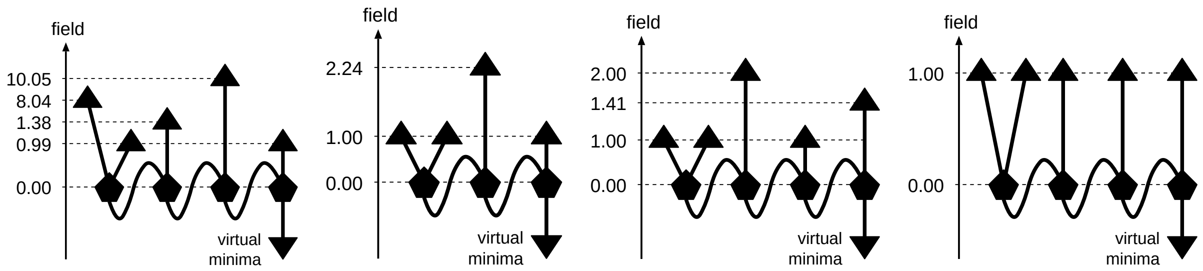
For the opacity transfer function, we define the critical field value as the scalar field value that corresponds to a critical point. The actual opacity transfer function highlights the critical isosurfaces that correspond to m_i critical field values $cv_0 \cdots cv_{m_i-1}$ at time step i. Furthermore, to highlight each of the individual critical isosurfaces, we assign smaller values to all the field domains, except local hat functions placed around to the critical field values $cv_0 \cdots cv_{m_i-1}$. In our framework for designing opacity transfer functions, because the outermost isosurface does not shrink as the field value decreases, we minimize the occlusion artifacts induced by the isosurface nested structure by decreasing the height of the hat functions by a fixed amount for cv_{m_i-1} through cv_0. Note that we reduce the number of critical points around 10 in order to visualize the topological change of a target volume dataset more clearly.

3.2. Haptic Transfer Functions

We can also design a 3-DOF haptic transfer function contributing to the practical understanding of a vector field and accentuated exposition of a pinpointed position of the given dataset. When a user moves the haptic stylus into the three-dimensional field, the stylus is assigned a force to move it along the vector field. At time step t, the force produced at a point p_t is defined as follows:

$$F(p_t) = k|\boldsymbol{v}(p_t)|\boldsymbol{v}(p_t), \tag{1}$$

where coefficient k denotes a compensating rate of the force and $\boldsymbol{v}(p_t)$ the vector value at the point p_t. For a snapshot dataset, this setting moves the stylus along the streamline derived from the dataset at that time. Repeating this three-dimensional force sensation for each time step allows the observer to haptically feel the time course of advection.



(a) time step 0 (b) time step 24 (c) time step 50 (d) time step 100

Figure 3: The volumetric skeleton trees extracted from wake turbulence dataset

4. RESULTS

To evaluate the effectiveness of our method, we applied it to a wake turbulence simulation dataset [8]. The platform used for the realization experiments was a standard PC (OS: Windows 7; CPU: Intel Xeon; clock speed: 3.46 GHz, RAM: 24 GB) connected to a Geomagic Touch haptic device, where the inputs were the 3-DOF stylus position information and the outputs were the three-dimensional forces. The code was implemented using C++ with the OpenGL and OpenHaptics Toolkits.

4.1. Wake Turbulence Dataset

Our target dataset is the wake turbulence dataset computed by measurement-integrated simulation [9], which utilizes actual data acquired from real phenomena to improve the accuracy of the numerical analysis. A lidar (light detection and ranging) data measured at takeoff of Boring 767 at Sendai Airport was used as the actual measurement data. This dataset has the pressure and velocity field. We also derived the vorticity field from the velocity field to analyze vortices more clearly. The spatial resolution of the dataset is 50×50 and the dataset contains 51 time steps.

4.2. Topological Skeletonization

First, we applied our topological skeletonization algorithm to the magnitude of vorticity vector field in the time-series wake turbulence dataset. Each of the snapshot dataset includes many critical points because our algorithm detects all of the critical points in a robust manner, although many of them may be irrelevant to the global structure. Therefore, we simplified the extracted VST until the number of critical points was reduced to 10.

Figure 3 shows the VSTs extracted from the magnitude of vorticity vector field of the wake turbulence dataset. From this result, it can be seen that the maximum values become smaller as time evolves. This indicates that the strength of the wake turbulence attenuates over time, but our method can robustly extract such weakening vortices.

4.3. Topology-Accentuated Volume Rendering

Next, we tried to visualize the dataset using volume rendering with our topology-accentuated visual transfer function. In order to explore the relationship between the pressure field and the magnitude of the vorticity field, we designed a color transfer function based on the pressure field and an opacity transfer function based on the magnitude of the vorticity field. The top column in Fig. 4 shows visualization results by using our topology-accentuated volume rendering. Since these images represent two scalar fields, we can comprehend the topological structure and the relationship between these fields at the same time.

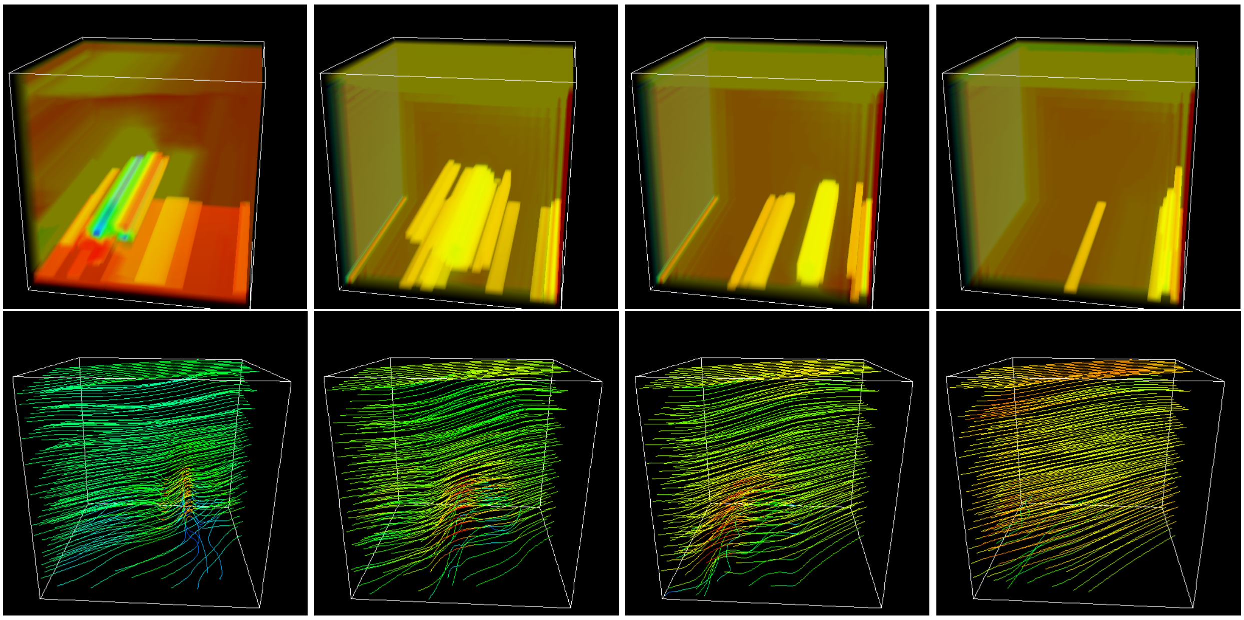
4.4. Realization

Finally, we attempted to sense the wake turbulence using our haptic transfer functions. Our system allows users to feel the strength and direction of the velocity field in synchronization with the topology-accentuated visualization, as shown in the top images in Fig. 4. The bottom images in Fig. 4 show the streamlines obtained from the wake turbulence dataset, which represent paths on which the stylus moves. From this experiment, we can intuitively understand two scalar values and one vector field simultaneously.

5. CONCLUSION

In this paper, we proposed a realization method that combines haptization with visualization. We applied our method to a time-varying three-dimensional wake turbulence dataset. Our experimental evaluations suggest that this method facilitates more intuitive analyses of wake turbulence datasets compared with previous methods that rely solely on visualization.

We plan to refine our haptic transfer function for a 6-DOF haptic device to sense a flow field in a more intuitive manner. In addition, we will conduct more case studies, such as large-scale datasets, to demonstrate the feasibility of the proposed method.



(a) time step 0 (b) time step 24 (c) time step 50 (d) time step 100

Figure 4: Visualization results: Top: our topology-accentuated volume rendering of the pressure field and the magnitude of vorticity field, and Bottom: streamlines on which the stylus moves.

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