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Current Trends for 4D Space-Time Topology for Semantic Flow Segmentation

Krešimir Matković [a], Alan Lež [a], Helwig Hauser [b], Armin Pobitzer [b], Holger Theisel [c], Alexander Kuhn [c], Mathias Otto [c], Ronald Peikert [d], Benjamin Schindler [d], Raphael Fuchs [d]

[a] *VRVis Research Center, Vienna, Austria*
[b] *University of Bergen, Norway*
[c] *University of Magdeburg, Germany*
[d] *ETH Zurich, Switzerland*

1. Introduction

Recent advances in computing and simulation technology promote the simulation of time-dependent flows, i.e., flows where the velocity field changes over time. The simulation of time-dependent flow is a more realistic approximation of natural phenomena and it represents an invaluable tool for scientists and practitioners in multiple disciplines, including meteorology, vehicle design, and medicine. Flow visualization, a subfield of scientific visualization, is one of several research areas which deal with the analysis of flows. There are many methods for the analysis of steady flows, but the extension to the time-dependent case is not straight forward. The SemSeg project, a FET-Open project in the 7th Framework programme, attempts to provide a solution for the semantic segmentation of time-dependent flows. It aims at the formulation of a sound theoretical mechanism to describe structural features in time-dependent flow. In this paper, we briefly summarize recent research results from the SemSeg project. Several different approaches are pursued in the project, including methods based on the finite-time Lyapunov exponent (FTLE), methods based on vector field topology (VFT), and interactive visual analysis (IVA) methods. Uncertainty visualization and the interactive evaluation of methods are helping in evaluating the results.

2. Selected Current Research in SemSeg

Vector field topology (VFT) is a well-established methodology for analyzing and visualizing velocity field datasets. Its power lies in the automatic and parameter-free extraction of flow structures that have proven meaningful in a wide range of application domains. Its limitation, however, is the restriction to steady flow. This was addressed, in parts, by using moving frames of reference for the local application of VFT, for example, based on optimality criteria [1].

Uncertain vector field topology. Flow data is usually obtained either by measuring the actual physical process or by simulation. In both cases the results contain an inherent uncertainty, that evolves from measurement inaccuracies as well as from different parameter setting or using different simulation models. We present a technique to visualize the global uncertainty in steady 3D vector fields using a topological approach. We start from an existing approach for the 2D case and extend this into 3D space. In addition, we develop an acceleration strategy to detect sink and source distributions. Having these distributions, we use overlaps of their corresponding volumes to identify separating structures and saddles. As part of the approach, we introduce uncertain saddle and boundary switch connectors and

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provide algorithms to extract them. For the visual representation, we use multiple direct volume renderings and test our method on a number of synthetic as well as real-world datasets [2]. A popular alternative to VFT is based on the finite-time Lyapunov exponent (FTLE). The ridges of this scalar quantity indicate flow structures, so-called Lagrangian coherent structures (LCS). These structures can be visualized without an explicit ridge extraction step. Analyzing LCS and the related geometrical trajectory properties allows for a deeper insight into the structure of time dependent flow phenomena.

Studying separation structures based on FTLE. For a thorough analysis such as the study of bifurcations, ridges are necessary. We compare several ridge definitions and developed a novel method [3] which exploits properties of FTLE fields. It avoids one order of numerical differentiation and results in higher quality ridge surfaces. Coherent flow behavior, and separation, as its dual behavior, are important features in flow fields. The currently most common approach to detect such behavior makes use of the FTLE, which is, informally speaking, the maximal local separation rate. We developed a filter that distinguishes between separation due to different flow directions and from separation due to different flow speeds [4]. The filter follows the geometric intuition behind the original definition of FTLE.

Computing the FTLE without the flow map gradient. Existing methods for the computation of FTLE either rely on an approximation of the flow map gradient, or they use frequent renormalization steps during the integration process. This poses a number of challenges which are due to the fact that this gradient shows an exponential growing or shrinking with integration time. We developed a novel method for computing FTLE of 2D unsteady vector fields which uses exclusively measures that are linearly growing with integration time. Using this approach the evolving FTLE can be reformulated as an ODE and obtained by a numerical integration of a 7D vector field.

Scale-space aware analysis of time-dependent dynamics. Commonly used feature extraction methods tend to have a rich response for complex, e.g., turbulent flows. Using classical image processing approaches, based, e.g., on size or the vicinity of two features, the output is reduced, which, however, does not necessarily respect the underlying physics. We propose the use of Proper Orthogonal Decomposition (POD) to decompose the flow field according to its kinetic energy to construct an approximation of the field, representing the largest energy-scales, and apply feature extraction in the sequel [5]. This guarantees that the large-scale dynamics of the flow are represented in the final output. By using a scale-space approach to both FTLE computation and ridge extraction [6], we were able to address the dilemma of either excessive computing time or error due to gradient underestimation.

Interactive Visual Analysis. Besides the above described automatic methods we also use interactive visual analysis (IVA) in order to understand flow phenomena. As simulation datasets get large, the fully automatic methods are no longer sufficient. We have developed a pathline explorer, a tool for the interactive visual analysis of time-dependent flows. The main idea is to compute pathlines and pathline attributes (some of them are scalar and others are functions of time or of the position along the pathline), and then to interactively explore the new dataset. The first tests were done using an exhaust manifold case from automotive industry [7]. Interactive visual analysis will be also used to compare results from various automatic flow segmentation methods.

3. Outlook and Acknowledgments

Based on the here presented research, we are looking forward to new research questions, including the analysis of tensors on unsteady flows as well as streakline-based approaches.

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