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

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1. INTRODUCTION

Recent advances in computing and simulation technology allow simulation of time dependent flows. These are flows where underlying vector field changes in time. The simulations of time dependent flows are a more realistic approximation of natural phenomena and they represent an invaluable tool for scientists in numerous disciplines, such as meteorology, car or airplane design, or medicine.

Flow visualization, a subfield of scientific visualization is one of several research communities which deals with analysis of flows. There are many methods for analysis of steady flows, but the extension to the time dependent case is not straight forward. The SemSeg project is a FET Open project which tries to come closer to an universal solution for 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 project. Several approaches are being pursued in the project, such as, methods based on the Finite Time Lyapunov Exponent (FTLE), Vector Field Topology (VFT) based methods, or interactive visual analysis methods. Uncertainty visualization and interactive evaluation of various methods are helping in evaluating current 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 is the restriction to steady flow. This was addressed in a recent paper [1] where we proposed to use moving frames of reference for local application of VFT. We defined criteria for the optimal choice of such moving frames.

Uncertain vector field topology.

Flow data is usually obtained either by measuring the actual physical process or by simulation. In both cases the results might contain an inherent uncertainty, that evolves from measurement inaccuracies as well as different parameter setting or using different simulation models.

We present a technique to visualize global uncertainty in stationary 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 provide algorithms to extract them. For visual representation, we use multiple direct volume renderings and tested our method on a number of synthetic and real data sets.

A popular alternative to VFT is based on the finite-time Lyapunov exponent (FTLE), a scalar quantity the ridges of which indicate flow structures, so-called Lagrangian coherent structures (LCS). These structures can be visualized without an explicit ridge extraction step, e.g., by colored slices or direct volume rendering. Analyzing Lagrangian Coherent Structures (LCS) and the related geometrical trajectory properties allow for deeper insight into the structure of time dependent flow phenomena.

Studying separation structures based on FTLE.

However, for further analysis such as the study of bifurcations, ridges are necessary. We compared several ridge definitions and developed a novel method [7] 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 Finite Time Lyapunov Exponent (FTLE), which is, informally speaking, the maximal local separation rate. In recent work we developed a filter that allows to differentiate between separation due to different flow directions and separation due to different flow speeds [5]. The filter follows the geometric intuition behind the original definition of FTLE as described by Haller [3] and uses information that is inherent to it. We demonstrate the effect of the proposed filtering on both synthetic and simulated data.

Computing the FTLE without the flow-map gradient.

Existing methods for FTLE computation either rely on an approximation of the flow map gradient, or they use frequent renormalization strategies 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. The resulting scheme has been applied to a set of analytical and simulated data sets together with a discussion about advantages and limitations in comparison to conventional FTLE computations.

Scale-space aware analysis of time-dependent dynamics.

Feature extraction, in general, is an important topic for flow analysis. A lot of the commonly used feature extraction methods tend to have a rich response for complex, e.g., turbulent, flows. Using classical image processing approaches, e.g., size or vicinity of two features, to reduce the output does, however, not necessarily respect the underlying physics. We propose the use of Proper Orthogonal Decomposition to decompose the flow field according to its kinetic energy, construct an approximation of the field representing the largest energy-scales and apply feature extraction in the sequel [6]. This guarantees that the large-scale dynamics of the flow is represented in the final output. We investigate the impact of the proposed approximation on both local and integration-based feature extraction providing local and global error statistics using simulation data.

By using a scale-space approach to both FTLE computation and ridge extraction, we were able to address two parameter issues. One parameter, the spatial sampling width, causes the dilemma of either excessive computing time or error due to gradient underestimation. The other parameter, the finite time inherent in the FTLE calculation, affects the resulting structures. Our scale-space approach [2] offers solutions to both problems.

Interactive Visual Analysis.

Besides above described automatic methods we also use Interactive Visual Analysis in order to understand various flow phenomena. As simulation data gets large the automatic methods alone are not enough any more. We have developed a path line explorer, a tool for interactive visual analysis of time dependent flows by means of interactive visual analysis. The main idea is to compute pathlines and various pathlines' attributes (some of them are scalar and some are functions of time or of position along pathline), and then to interactively explore the new dataset. The first tests were done using an exhaust manifold case from automotive industry [4]. We are currently further pursuing the idea and we are trying to find a generally useful set of pathlines' parameters. At the same time we are improving the interactive visual analysis itself by adding many comparison support tools and by integrating automatic optimization methods.

Besides analysis of flow itself, the interactive visual analysis will be used to compare results form various automatic flow segmentation methods. It will be used as an evaluation tool, and we expect to be able to interactively navigate through the complex space of automatic segmentation results. We also expect that Interactive Visual Analysis will make it possible to efficiently combine various methods in order to understand flow phenomena.

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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More information about the SemSeg project is available from URL www.SemSeg.eu

4. REFERENCES

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