

On the Way Towards Topology-Based Visualization of Unsteady Flow – the State of the Art

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Abstract

Vector fields are a common concept for the representation of many different kinds of flow phenomena in science and engineering. Topology-based methods have shown their convenience for visualizing and analyzing steady flow but a counterpart for unsteady flow is still missing. However, a lot of good and relevant work has been done aiming at such a solution.

We give an overview of the research done on the way towards topology-based visualization of unsteady flow, pointing out the different approaches and methodologies involved as well as their relation to each other, taking classical (i.e. steady) vector field topology as our starting point. Particularly, we focus on Lagrangian Methods, Space-Time Domain Approaches, Local Methods, and Stochastic and Multi-Field Approaches. Furthermore, we illustrated our review with practical examples for the different approaches.

1. Introduction

The concept of *flow* plays a central role in many fields of engineering. Classical application fields are, for example, the automotive and aviation industry. However, the same concepts are used in the simulation of flow in turbines of power plants, blood flow in vessels, propagation of smoke in buildings, and weather simulations, just to mention a few. The visualization of data gained from the simulation/measurement of such processes is therefore relevant for the user domain since such visualization eases the understanding of complex phenomena.

Topological methods for flow visualization have been researched throughout the last decade and a specific conference, called *Topological Methods in Visualization* (TopoInVis), has been established [HHT07, HPS08].

The general setting for topological methods is more general than described above. Namely, any vector field, interpreting it as the rate of change of a certain quantity, might be visualized using such methods. Then, the vector field represents the states of a dynamical system governed by differ-

ential equations. In such a setting the evolution of a certain point/configuration can be described mathematically as solutions of the differential equation

$$\dot{\mathbf{x}}(t) = \mathbf{v}(\mathbf{x}(t), t).$$

Because of the tight relation of this model to fluid dynamics the vector field \mathbf{v} is often referred to as *flow*. Notice, however, that the vector field needs to fulfill additional equations (Navier-Stokes) in order to represent a flow in fluid-dynamical sense. If the vector field \mathbf{v} does not depend on the variable t the system is said to be autonomous, otherwise non-autonomous. Equivalently, the expressions *steady* and *unsteady* (or simply *time-dependent*) flow are used.

In the study of such flow/dynamical systems certain features such as critical points, separatrices and closed orbits play an important role. In 1989, Helman and Hesselink introduced these concepts to the visualization community under the name of *vector field topology* [HH89a]. Methods for visualizing steady flow fields, especially planar flow fields, have achieved a high level of proficiency, while the un-

steady case is still challenging and by no means complete [LHZP07, PVH*02, LHD*04, SJWS08].

Since vector field topology (VFT) and feature extraction build a solid base for understanding and visualizing a given steady flow field, it is seemingly canonical to expect that those methods, with possible extensions, may yield the same facilities for unsteady flow.

In the remainder of this introduction we give a short overview and attempt to structure the field. A detailed discussion with many additional references is left to the respective sections, then.

Classical vector field topology (i.e., for steady flows) segments the flow in regions where trajectories show the same behavior when looking at the t -limits at $\pm\infty$. This fact needs special attention when taking the step from steady to unsteady flow: in a steady field a finite number of data can be used to determine behavior at an arbitrary instance of time. For unsteady fields, this is not true: the information available is usually restricted to a certain time-window. This means that, in general, no statement about the asymptotic behavior of the trajectories is possible. Visualizing time-dependent flow essentially poses different research challenges as compared to visualizing steady flow.

Despite this, the first attempts of approaching a topology-based visualization of unsteady flow interpreted the unsteady field as a stack of steady flow fields. This induced the idea that a VFT-like segmentation of unsteady flow can be achieved using the already known methods for discrete time slices and identifying corresponding structures in subsequent time steps. Methods for the topology-based visualization of unsteady flow based on trajectories in individual time steps can be classified as tracking methods (tracking in time). In section 3 we give an overview over the of the research done in this direction. The trajectories in a fixed time step $t = t_0$ are solutions of the following first-order ordinary differential equation

$$\dot{\mathbf{x}}(s) = \mathbf{v}(\mathbf{x}(s), t_0), \quad \mathbf{x}(t_0) = \mathbf{x}_0. \quad (1)$$

These solutions are called *streamlines*. Notice that the integration time s is not related to the time t on which the vector field \mathbf{v} depends. The t -time becomes in that case a parameter of the system. Even though this is no issue from a purely mathematical point of view, the s -time still lacks physical interpretation. Following a streamline means “freezing” the flow at some instance of time t and integrating (along a “virtual” time s) to $\pm\infty$. Only in special cases particles follow streamlines in realistic scenarios (and usually for a while only, if at all).

A promising approach is to investigate the behavior of *pathlines*, i.e., the solutions of

$$\dot{\mathbf{x}}(t) = \mathbf{v}(\mathbf{x}(t), t), \quad \mathbf{x}(t_0) = \mathbf{x}_0. \quad (2)$$

The solutions of this equation describe the theoretical path of massless particles through the flow.

Another approach that uses the path of massless particles is the investigation of so-called *streaklines*, defined as

$$\mathbf{x}_t(\tau) = \mathbf{x}_\tau(t) \quad (3)$$

where \mathbf{x}_τ is the solution for the initial value problem

$$\dot{\mathbf{x}}(s) = \mathbf{v}(\mathbf{x}(s), s), \quad \mathbf{x}(\tau) = \mathbf{x}_0 \quad (4)$$

evaluated at $s = t$. This describes mathematically the common experimental setup of injecting a marker (say dye) in a flow at a fixed spatial location \mathbf{x}_0 for the time interval $[t_0, t]$. The function \mathbf{x}_t is then a parameterization of the curve consisting of the injected particles at time t , more precisely, $\mathbf{x}_t(\tau)$ is the position of the particle seeded at $\tau \in [t_0, t]$ at time t .

The concepts of path- and streakline are essentially different from the concept of streamlines in unsteady flow. Their focus is the behavior of one or more moving particles. Therefore they can be classified as Lagrangian methods. We discuss these methods in section 4. However, applied to steady flow, which is of course a special case of unsteady flow, all three definitions yield the same trajectories.

In the context of this view on flow scenarios, structures that maintain their attracting (or repelling) nature over a relatively long time play an important role, since they influence all passing particles in a coherent manner. Along these lines, a scalar measure for the local separation behavior of the flow, the so-called finite-time Lyapunov exponents (FTLE), have gained attention in the visualization community [Hal01a]. The notion of *Lagrangian Coherent Structures* (LCS) recognizes that there are repeating patterns of motion in turbulent flows [DD04]. This phenomenon of repeated, similar structures has led to the assumption that understanding these coherent structures will give insight into the mechanisms of turbulence. There is no generally accepted definition of Lagrangian coherent structures until today, but one important notion is to identify them as the ridges of the FTLE field [Hal02].

Recently, a mathematical framework called *Feature Flow Field* has been introduced which can treat the concepts of path- and streamlines in a unified way [TS03]. The idea behind this approach is that the unsteady flow is transformed into a higher dimensional steady flow. Then the computation of path- and streamlines reduces to the computation of streamlines of some related vector fields. Classical vector field topology is not applicable to these fields, however, since they do not contain isolated critical points. Nevertheless, it is possible to capture parts of the topological information of the original vector field, e.g., critical points, periodic orbits, vortex axes, by constructing respective auxiliary vector fields. For different tasks different vector fields are needed. These and similar methods can be classified as space-time domain approaches and we discuss them in more detail in section 5.

As addressed above, the extraction of features is an important complement to VFT in the steady case (to be precise,

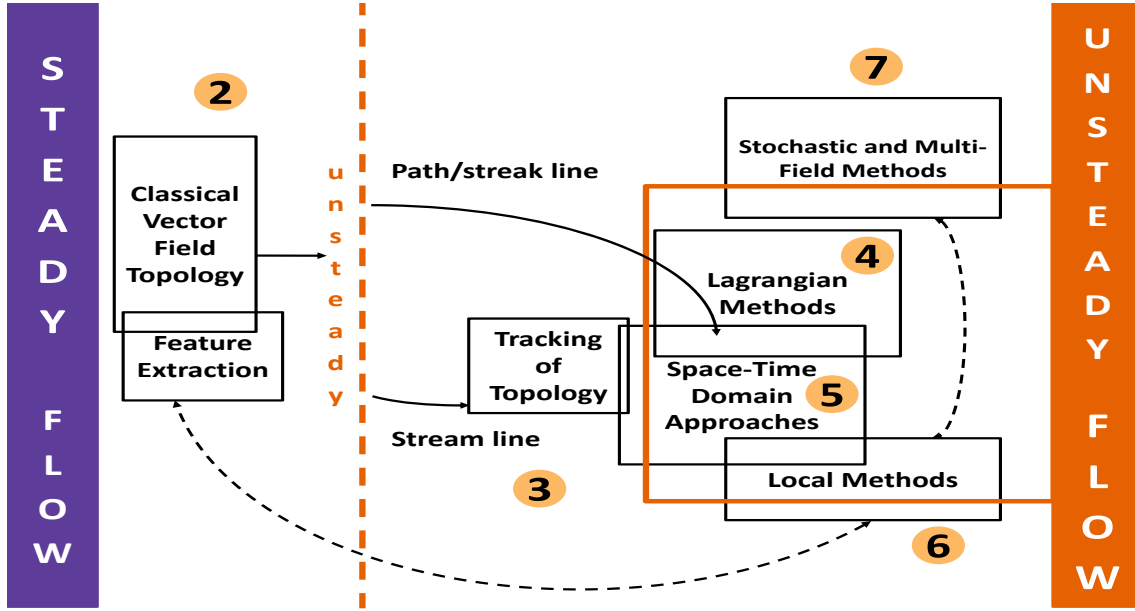


Figure 1: Approaches and methods used on the way towards topology-based unsteady flow visualization and their relations. Thematic overlap is represented by intersecting building blocks. Solid arrows represent conceptual relations and dashed arrows methodical. The orange square collects the current available brick stones that come closest to the topology-based visualization of unsteady flow. The numbers indicate the sections in which the respective building blocks are discussed.

the extraction of some features, e.g., critical points, is a step in computing the topology of a steady flow). Of course, it is desirable to extract the unsteady counterparts of the features in steady flow. Most of the methods for feature extraction are local methods, i.e., they use point-wise information. The actual extraction is carried out by methods also known from image processing. In contrast to methods that involve integration, most of these techniques can be used for unsteady vector fields (at least to a certain degree). Currently these methods focus mainly on vortex structures and separation and attachment lines. Local methods of that kind are discussed in section 6.

One problem that feature extraction suffers from is that the definition of such often involves parameters such as thresholds or time windows (which is also true for FTLE) or that the definition is not unanimous (e.g. as for vortices). Often features are not detected in the actual vector field but in a field derived from the original one and the detection of multiple features (or various definitions of the same feature-type) has to deal with multiple fields, consequently.

Since dealing with multiple features at once can be interpreted as dealing with multivariate data, the use of *Interactive Visual Analysis* (IVA) has been suggested [BMDH07]. The idea is to combine several feature detectors in order to investigate combinations of them. This is valuable both for extracting those features and for understanding the param-

eters that determine behavior that might be intuitively clear but not precisely defined.

Another opportunity offered by IVA is to detect correlations between different feature definitions. Furthermore, this method offers the possibility to meet the needs of the user domain more flexibly. An engineer, for instance, might be interested in additional properties (e.g., pressure, temperature, ...) of the medium, apart from the actual flow. On the other hand, engineers may use different models for the same situation, according to different tasks. IVA gives the opportunity to interactively investigate the relations between different variables/models using multiple views and linking+brushing.

One prerequisite regarding feature extraction is that the user has to be aware of which feature should be searched for. Recently, information theory based approaches were presented that are capable of detecting regions in which something extraordinary is likely to happen automatically [JWSK07].

Finally, one may be interested in displaying both flow topology and features. Unfortunately, it is known that separatrices may cross features (e.g. vortices) and therefore split them. *Stream-* and later *pathline predicates* offer a possibility to combine several feature detectors and flow topology in order to refine the latter, while keeping features intact [SS07, SGSM08].

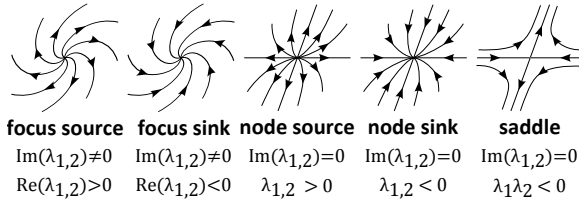


Figure 2: Types of first-order critical points in 2D

IVA and the above mentioned methods addressing similar problematics will be discussed in section 7.

In accordance with this brief overview of the building blocks available on the way towards topology-based visualization of unsteady flow, the rest of the paper is structured as following: (2) Classical Vector Field Topology, (3) Tracking of Topology, (4) Lagrangian methods, (5) Space-Time Domain Approaches, (6) Local Methods, (7) Stochastic and Multi-Field Approaches, and (8) Discussion and Conclusions.

Figure 1 gives a graphical overview of the classes of approaches and methods and how they are related to each other as well as a graphical table of content of this article.

2. Classical Vector Field Topology

This section gives a brief overview on both historical and theoretical aspects of classical, i.e. steady, vector field topology as well as its application in visualization and further applications.

2.1. History

The theory of *dynamical systems* goes back to the 19th century work of Henri Poincaré [Poi92]. A modern introduction can be found e.g. in Guckenheimer and Holmes [GH83]. In our context the case of deterministic, continuous, and autonomous dynamical systems is most interesting, since such systems can be used to formulate velocity fields of a steady fluid flow. Many patterns in a flow can be described and analyzed by concepts from dynamical systems such as *critical points*, *separatrices* and *periodic orbits*. Perry and Chong [PC87] gave a comprehensive overview of such 2D and 3D flow patterns. Helman and Hesselink introduced these methods to the scientific visualization community, and under used them the notion of *vector field topology* for the visualization of computed and measured velocity fields, first in 2D [HH89b] and later in 3D [HH91]. Vector field topology was further popularized both by Asimov’s excellent tutorial [Asi93] and by Globus et al.’s TOPO module [GLL91] for NASA’s FAST visualization software. Over two decades, topologically-based flow visualization has been an active research topic. A state-of-the-art report [LHZP07] was published in 2007.

2.2. Background

Let $\mathbf{v}(\mathbf{x})$ denote a steady velocity field. Then a streamline, i.e., the solution of the initial value problem given in equation (1), exists uniquely if $\mathbf{v}(\mathbf{x})$ is Lipschitz-continuous [GH83], which is the case for discrete data interpolated with any of the popular schemes. Vector field topology now deals with the two kinds of singular streamlines, namely *stationary points* and *periodic orbits*. These singularities are of particular interest if they are *isolated*. A sufficient condition for an isolated stationary point, called a critical point, is that the velocity gradient tensor is regular at this point (while its velocity is vanishing). Similarly, a periodic orbit is isolated if the gradient tensor of the Poincaré map is regular [GH83]. For these first-order singularities, a type classification can be made by analyzing the eigenvalues of the gradient tensor. For 2D vector fields, there are the five possible types *saddle*, *node source*, *node sink*, *focus source* and *focus sink*, plus transitional types which are structurally unstable, see Fig. 2. In the special case of a divergence-free 2D vector field, there are no sources or sinks, but instead the center is a structurally stable type.

Type classifications exist also for first-order critical points in 3D fields and for first-order periodic orbits in 3D fields [Asi93]. Finally, higher-order singularities can be further analyzed. Depending on higher-order derivatives, the singularity (critical point or periodic orbit) can still be an isolated one. A classification of higher-order critical points in 2D was given by Firby and Gardiner [FG82]. Scheuermann et al. [SHK*97] introduced a visualization of higher-order critical points.

The *topological skeleton* is obtained by computing all singularities plus their lower-dimensional invariant manifolds. In 2D fields only the saddle type critical points have 1D invariant manifolds. These are the so-called *separatrices*, i.e. the streamlines converging in either positive or negative time to a saddle point. As the topological skeleton contains most of the topological information of a (steady) vector field, it is a concise characterization of the vector field. The separatrices divide regions of different flow behavior and they often have physical relevance. In 3D velocity fields, such topological structures can indicate phenomena like flow separation or vortex axes.

2.3. Visualization methods based on vector field topology

A considerable amount of research has been done to extract, analyze, modify and visualize the topology of steady vector fields. Several approaches can be used to extract critical points. In piecewise linear fields, the zeros can be computed explicitly. In more general settings, one might use a Newton-Raphson approach [Kel03]. An octree-like method is presented by Mann et al. [MR02]: they compute the index of each cell and a non-zero index triggers a recursive sub-

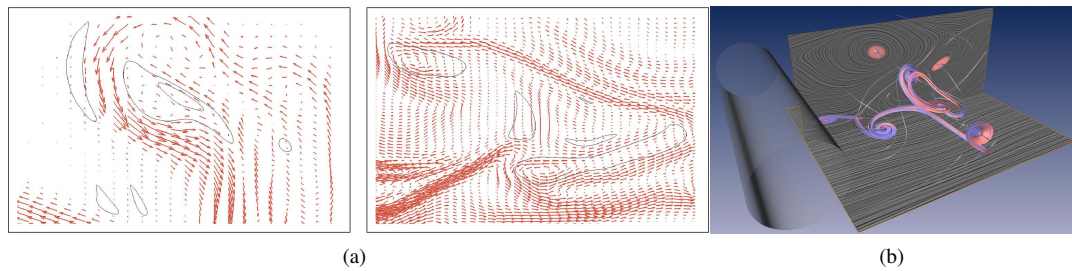


Figure 3: (a) Periodic orbits detected in a turbulent 2D flow field (image courtesy of Wischgoll et al. [WS01]); (b) Visualization of saddle connectors in a flow behind a circular cylinder (image courtesy of Theisel et al. [TWHS03]).

division. Trotts et al. [TKH00] introduce the notion of critical points at infinity to find new separatrices. The curvature of streamlines in the proximity of critical points has been studied by Theisel and Weinkauff [The95, WT02] for 2D and 3D vector fields. Mahrous et al. [MBS*04] present an algorithm to extract separation surfaces to segment topologically steady 3D flow. They do this sampling the vector field by streamlines, deriving a segmented data set from the original field and using this data set for the construction of the separation surfaces. In a later paper Mahrous et al. present an improved algorithm [MBHJ03]. Regions of different flow behavior on the boundary of 2D vector fields as well as the corresponding separatrices have been considered by de Leeuw and van Lier [dLvL99a] and Scheuermann et al. [SHJK00].

A first approach to detecting periodic orbits was given by Wischgoll and Scheuermann [WS01] which uses the underlying grid structure of a piecewise linear vector field: each grid cell is analyzed concerning the re-entering behavior of streamlines that start at its boundaries. Figure 3(a) shows results obtained by this method. The method was extended to 3D [WS02] by the same authors.

Peikert and Sadlo discuss periodic orbits in 3D vector fields [PS07b]. Li et al. [LVRL06] discuss how to represent higher-order critical points on triangular surfaces using a carefully chosen triangulation and interpolation. Scheuermann et al. [SHK*97, SKMR98] explained visualization approaches for planar flows. An algorithm for computing 2D invariant manifolds of singularities in 3D vector fields was presented by Krauskopf and Osinga [KO99] where the surface mesh is organized in geodesic circles. Theisel et al. [TWHS03] proposed to display only pairwise intersections of such streamsurfaces, known as saddle connectors or heteroclinic orbits. Figure 3(b) shows saddle connectors in a flow behind circular cylinder. Peikert and Sadlo [PS09] presented a streamsurface algorithm that robustly handles starting from and converging to singularities.

Separation and attachment lines play an important role considering the flow around and on bodies in 3D flow fields. Kenwright [Ken98] and Kenwright et al. [KHL99] present methods to extract attachment and separation lines. Wiebel

et al. [WTS09] present a robust method to extract separation surfaces from these lines using topology extraction in cross sections of the flow.

2.4. Further applications of topological features

As described by Theisel et al. [TRW07] topological features of vector fields have not only proved to be a valuable visualization tool, they can also be used for other tasks in processing vector fields.

Compressing vector fields To simplify and compress large and complex flow data sets, methods based on topological concepts allow for more efficient computational handling and transmission. Compression in this context means to reduce the amount of data while maintaining important structures. Lodha et al. [LRR00, LFR03] introduce a compression technique for 2D vector fields which prohibits strong changes of location and Jacobian matrix of the critical points. Theisel et al. [TRS03b] present an approach which guarantees that the topology of original and compressed vector field coincides both for critical points and for the connectivity of the separatrices. It is shown that even under these strong conditions high compression ratios for vector fields with complex topologies are achieved.

Topological simplification of vector fields The topological skeleton of a vector field may become very complex due to the presence of noise. The reduction of unimportant topological features can be accomplished by simplifying the resulting topological structure. Besides smoothing of the vector field before extracting the topology as described by De Leeuw et al. [dLvL99b], more involved techniques start with the original topological skeleton and repeatedly apply local modifications of the skeleton and/or the underlying vector field in order to remove unimportant critical points. De Leeuw and van Lier [dLvL99a] measure the importance of a critical point by computing the area from which the flow ends in forward or backward integration. Based on this area metric, the unimportant critical points are repeatedly collapsed to more important critical points in the neighborhood. The system described by De Leeuw et al. [dLvL99b]

finds couples of first order critical points by considering distance and connectivity of them. Then less important critical points are pairwise collapsed. Tricoche et al. [TSH01a] use a similar approach but provide a way of consistently updating the underlying vector field. Further the simplification of the topology of a 2D vector field is accomplished by replacing clusters of first order critical points with a higher order critical point. Weinkauff et al. [WTS*05] extend this to 3D vector fields. Theisel et al. [TRS03a] solve the coupling problem of critical points by a feature flow field approach which will be explained in section 5.2 in further detail.

Topological comparison of vector fields The definition of useful metrics on vector fields plays a crucial role in the majority of applications mentioned above. The first approaches on metrics (distance measures) of vector fields as proposed by Heckel et al. [HWHJ99] and Telea et al. [TvW99] consider local deviations of direction and magnitude of the flow vectors in a certain number of sample points. These distance functions give a fast comparison of the vector field but do not take any structural information of the vector fields into consideration. A first approach to define a topology based distance function was given by Lavin et al. [LBH98]. Given two vector fields \mathbf{v}_1 and \mathbf{v}_2 , all critical points are extracted and coupled. Then the distance of the vector fields is obtained as sum of the distances of the corresponding critical points in \mathbf{v}_1 and \mathbf{v}_2 . To compute the distance between two critical points, a number of approaches exist [LBH98, TW02]. To couple the points, Theisel et al. [TRS03c] proposes to use feature flow fields. A general demonstration of this comparison on real data sets is given by the same authors [TRW07].

Constructing vector fields Besides using a simulation or measurement process for data acquisition the vector field data can also be obtained by construction. Theisel et al. [The02] present an approach oriented at methods from the CAGD (Computer Aided Geometric Design) context. First, a topological skeleton of a vector field is constructed by a number of control polygons. Second, a piecewise linear vector field of exactly the specified topology is automatically created. An approach for constructing 3D vector fields is presented by Weinkauff et al. [WTHS04]. There, a number of specified control polygons is used to determine location and characterization of first or higher order critical points and the saddle connectors. The resulting skeleton is used to construct a piecewise linear vector field. In application to 3D surfaces topology-based construction and editing of vector fields can be used to enrich surfaces with additional information. Thus vector fields have been used for generating non-photorealistic visualizations, like painterly renderings or pen-and-ink visualizations, and remeshing of the underlying surface [PZ07]. Zhang et al. [ZHT07] present a system to interactively create and edit 2D static vector field which can be applied to the limited domain of a 3D surfaces. Recently topological methods have been successfully applied

to extract salient features on discrete 3D surfaces as shown by Weinkauff et al. [WG09].

3. First Approaches towards Unsteady Flow Fields: Tracking of Topology

First attempt to cope with time-dependent velocity fields where done by looking at the instantaneous velocity fields. Taking this as starting point some extensions to classical vector field topology are available. However, newer research shows clearly the limitations of this approach.

3.1. Tracking of singularities

Instantaneous topology extraction can be combined with tracking of the singularities over time. Tricoche et al. [TSH01b, TWSH02] present a method for tracking the location of critical points and detecting local bifurcations such as fold bifurcations and Hopf bifurcations. This approach works on a piecewise linear 2D vector field and computes and connects the critical points on the faces of a prism cell structure, which is constructed from the underlying triangular grid. An extension to 3D has been given by Garth et al. [GTS04] together with a visualization of the paths in space-time of the critical points. Wischgoll et al. [WSH01] track closed streamlines over time by applying a contouring and connecting approach. At each time step closed streamlines are detected independently of each other, then the corresponding lines in adjacent time steps are connected.

3.2. Deficiency of vector field topology for unsteady flow

There are certain extensions of vector field topology to time dependent velocity fields. An obvious approach is to look at the instantaneous velocity field. However, streamlines do not capture the temporal change of the flow. In the context of experimental flow visualization researchers noted very early that a correct frame of reference is important to extract meaningful structures. Perry and Tan [PT84] suggested to extract patterns as 'seen' by an observer who is moving with the eddies. They used correlation technique to compute the velocity of an eddy and found the resulting measurements to be quasi-steady. Later, Perry and Chong [PC94] stated clearly that topological information is only meaningful in a Galilean reference frame in which the velocity field is nearly steady. This implies that vector field topology is not applicable if such a frame does not exist.

While known in theory, practice largely ignored this problem until when Shadden et al. [SLM05] gave with the "double gyre" an example of an unsteady flow for which a saddle type critical point substantially deviates from the actual point of flow separation. Recently, Wiebel et al. [WCW*09] demonstrated the failure of vector field topology to find moving attractors in simulation data of a rotating liquid suspension. They suggested a procedural solution based on the evolution of density of virtual particles seeded in the flow.

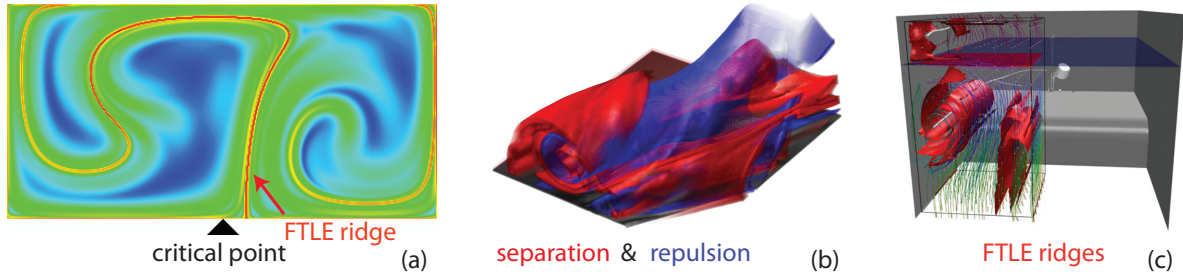


Figure 4: Applications of FTLE to visualization. (a) In the double gyre example the critical point disjunct to the FTLE ridge separating different regimes of the flow (image created following Shadden et al. [SDM06]). (b) Volume rendering of the FTLE field shows the regions of locally maximal attracting and repelling behavior (image courtesy of Garth et al. [GGTH07]). (c) Extraction of ridges from the FTLE field allows additional processing and filtering to concentrate on the salient features of the flow (image courtesy of Sadlo et al. [SP07a]).

4. Lagrangian Methods

In the Lagrangian point of view the fluid is described by the motion of its particles. Since the analysis is based on trajectories of one or multiple particles such methods are inherently suited for unsteady flows.

4.1. The Finite-Time Lyapunov Exponent

The finite-time Lyapunov exponent (FTLE), by some authors referred to as direct Lyapunov exponent (DLE) [Hal01b], is a measure for the stretching of an infinitesimal neighborhood along a finite segment of a flow trajectory.

More formally, let $\mathbf{v}(\mathbf{x}, t)$ denote the velocity field. Then, a trajectory $\mathbf{x}(t)$ starting from \mathbf{x}_0 at time t_0 is the solution of an initial value problem (see also Equation 2). The set of all trajectories provide the *flow map* $\mathbf{x}(\mathbf{x}_0, t_0, t)$ that maps the position at time t on the trajectory started at time t_0 from \mathbf{x}_0 . By computing the flow map gradient and left-multiplying it with its transpose, the (right) *Cauchy-Green deformation tensor field* [Mas99] is obtained as

$$\mathbf{C}_{t_0}^t(\mathbf{x}_0) = \left[\frac{\partial \mathbf{x}(\mathbf{x}_0, t_0, t)}{\partial \mathbf{x}_0} \right]^T \left[\frac{\partial \mathbf{x}(\mathbf{x}_0, t_0, t)}{\partial \mathbf{x}_0} \right]. \quad (5)$$

From this, the (*maximum*) FTLE is defined as

$$\text{FTLE}_{t_0}^t(\mathbf{x}_0) = \frac{1}{2(t-t_0)} \ln \lambda_{\max}(\mathbf{C}_{t_0}^t(\mathbf{x}_0)), \quad (6)$$

where $\lambda_{\max}(\mathbf{M})$ denotes the maximum eigenvalue of \mathbf{M} [Hal01b].

In the limit $t \rightarrow t_0$ the FTLE is the *maximum principal rate-of-strain*, i.e. the maximum eigenvalue of the rate-of-strain tensor

$$\mathbf{S} = [\nabla \mathbf{v}(\mathbf{x}_0, t_0)]^T [\nabla \mathbf{v}(\mathbf{x}_0, t_0)]. \quad (7)$$

In the limit $t \rightarrow \infty$, the FTLE is the (standard) Lyapunov

exponent which is independent also of t_0 . Discovered by A. M. Lyapunov in the 1890's, the Lyapunov exponents became popular in the 1970's for the analysis of chaos and predictability in dynamical systems. The finite-time variant was used [GSO87, YN93] originally also for predictability of systems, especially for atmospheric models. In a seminal paper [Hal01a], Haller applied FTLE to velocity fields of fluid flow and revealed their relationship to the Lagrangian coherent structures (LCS), which can provide the information on flow separation similar to the separatrices of vector field topology, however often also correctly for strongly time-dependent flow. In his subsequent paper [Hal02], he identified the *ridges* of the FTLE as LCS. In Figure 4 we show some applications of FTLE.

Shadden et al. [SLM05] applied FTLE to the “double gyre” example (where vector field topology fails) and various other example flow fields in 2D. They showed visually that particles seeded near the FTLE ridges do not cross them. Another counter-example for vector field topology was suggested by Wiebel et al. [WCW*09] where the FTLE peak was shown deviate much less from the observed (moving) attractor than the topological sink.

Garth et al. presented an algorithm for FTLE computation in 2D transient flow [GLT*07]. They proposed to approximate 3D FTLE by 2D FTLE computed in the orthogonal space of the velocity vector [GGTH07]. The computation of ridges is avoided by using a direct volume rendering approach. With a variation of this technique Garth et al. [GWT*08] computed 2D FTLE on offset surfaces of solid boundaries resulting in a visualization of flow separation and flow reattachment. Sadlo et al. addressed the problems of efficient computation of height ridges of FTLE [SP07a] and of tracking FTLE ridges over time by using a grid advection technique [SP09].

Comparisons of FTLE with other criteria in terms of suitability for visualization were made by several authors. Shad-

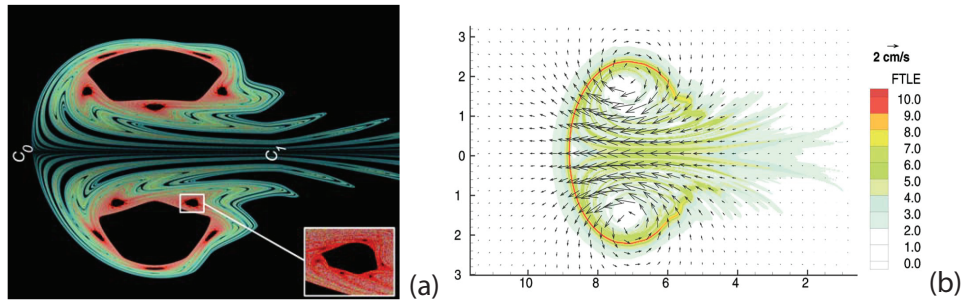


Figure 5: Analysis of a vortex ring. (a) Topological methods can benefit from the infinite integration time available and give detailed insight into regions of stability and folding structures of the flow (image courtesy of Peikert et al. [PS07a]). (b) Even though much less integration time is available the FTLE field can give insight into the structure of the vortex ring (image courtesy of Shadden et al. [SDM06]).

den et al. [SDM06] showed that FTLE is able to reveal the fine lobes of a chaotic vortex ring while producing temporally more consistent results than an approach based on vector field topology. In Figure 5 we compare VFT and FTLE. In (a) we can see that the possibility to integrate streamlines into a chaotic region of the flow for very long integration times allows to extract sharply defined regions of stability. In Figure 5(b) we can see that the restriction to a finite time domain is alleviated using FTLE to visualize the structure of the vortex ring.

In recent studies by Green et al. [GRH07] and Shi et al. [STW*08] FTLE is validated against other indicators of LCS in a number of analytical and numerical flow fields, and FTLE was found to generate more detail. In a study done by Sadlo et al. [SP07b], FTLE was shown to extract flow separation structures, but not the axes or centers of rotating flow. In comparison with vector field topology, this means that FTLE provides only partial information. In the example of a *spiral saddle critical point*, where vector field topology would give a 1D and a 2D invariant manifold that can be interpreted as a vortex axis and a separation surface, only the latter is reliably detected by FTLE.

Another current limitation of FTLE is that it requires the choice of a time window the effect of which has not been studied sufficiently. Also, the result is influenced by the definition of a ridge, given the choice of height ridges, watersheds, maximal curvature ridges [Ebe96] and others.

4.2. Other Lagrangian Feature Detectors

While FTLE in addition to its advantages it also has the aforementioned limitation to inform only about flow separation, other calculations can be performed in the Lagrangian frame that reveal other types of flow features. Basically, by computing the Cauchy-Green deformation tensor from the flow map gradient, the rotational part is discarded. However, to detect a vortex, this information is needed. Therefore, ei-

ther the flow map gradient must be used in a different way or a different type of temporal integration must be performed.

Cucitore et al.'s non-local vortex detector [CQB99] uses a reference frame that moves with a particle to be tested. In this frame, the path of a neighbor particle is calculated for a certain time window. Then, the distance of the end point from the origin is divided by the arc length of the path. Low values of this ratio indicate a vortex center. Haller proposed another vortex detector M_z [Hal05] that is objective, i.e. invariant not only under Galilean transforms, but also for rotating frames of reference. Finally, any local vortex detector designed for steady flow can be adapted to unsteady flow by applying a Lagrangian smoothing, i.e. by computing a weighted average of the quantity obtained for the same particle at several time steps. Lagrangian smoothing has been shown to be better than a purely steady analysis by Shi et al. [STH*07] and by Fuchs et al. [FPS*08].

Recently, several authors brought up the idea to adapt the definitions underlying vector field topology for unsteady velocity fields. Kasten et al. [KHNH09] propose minima of the acceleration magnitude, after a temporal smoothing in the Lagrangian frame, as a replacement for critical points in unsteady velocity fields.

5. Space-Time Domain Approaches

In order to be able to handle the problem of detecting features in time dependent data sets one way is to lift this problem into a higher dimension by interpreting the time as an additional axis and thereby assume the steady case again. This definition allows a clear definition of pathlines by means of streamlines in the lifted higher-dimensional case.

5.1. Streamlines and Pathlines

When dealing with a time-dependent vector field $\mathbf{v}(\mathbf{x}, t)$, we usually are interested in its spatiotemporal characteristics.

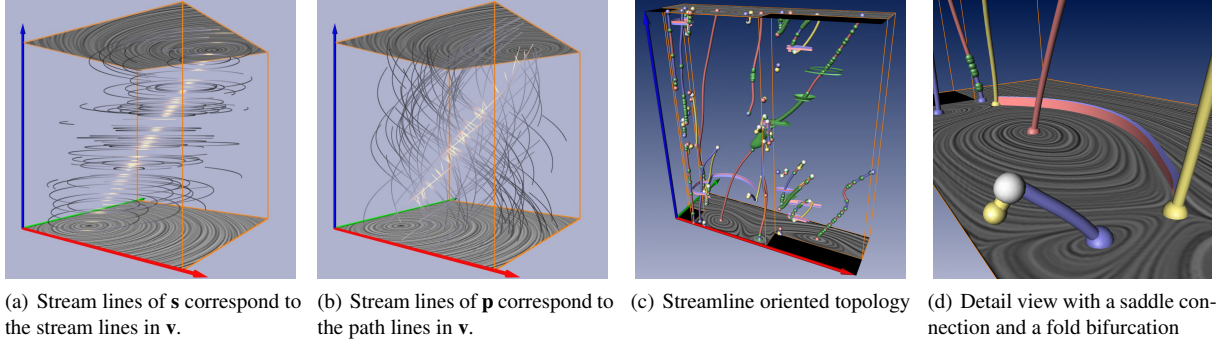


Figure 6: Streamlines (a) and pathlines (b) of a simple 2D time-dependent vector field obtained by linear interpolation of two steady 2D vector fields and shown as illuminated field lines. The extracted and visualized topological skeleton (c) and detailed structures (d) of the cavity data set (image courtesy of Theisel et al. [TWH505]).

As discussed in the introduction, several concepts can be used to explore those characteristics. In a specified space-time point $(\mathbf{x}_0, t_0) \in D$ we can start a *streamline* (cf. eq.(1)) or a *pathline*. The defining ODE system (2) can be rewritten as an autonomous system at the expense of an increase in dimension by one, if time is included as an explicit state variable:

$$\frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ t \end{pmatrix} = \begin{pmatrix} \mathbf{v}(\mathbf{x}(t), t) \\ 1 \end{pmatrix}, \quad \begin{pmatrix} \mathbf{x} \\ t \end{pmatrix}(0) = \begin{pmatrix} \mathbf{x}_0 \\ t_0 \end{pmatrix}$$

In this formulation space and time are dealt with on equal footing – facilitating the analysis of spatio-temporal features. Pathlines of the original vector field \mathbf{v} in ordinary space now appear as streamlines of the vector field

$$\mathbf{p}(\mathbf{x}, t) = \begin{pmatrix} \mathbf{v}(\mathbf{x}, t) \\ 1 \end{pmatrix} \quad (8)$$

in space-time. To treat streamlines of \mathbf{v} , one may simply use

$$\mathbf{s}(\mathbf{x}, t) = \begin{pmatrix} \mathbf{v}(\mathbf{x}, t) \\ 0 \end{pmatrix}. \quad (9)$$

This is valid for arbitrary space dimensions.

Figure 6 illustrates \mathbf{s} and \mathbf{p} for a simple example vector field \mathbf{v} . It is obtained by a linear interpolation over time of two bilinear vector fields.

Now the problem of finding a streamline or pathline oriented topology is reduced to finding the topological skeletons of \mathbf{s} and \mathbf{p} . Unfortunately, neither for \mathbf{s} nor for \mathbf{p} the classical vector field topology extraction techniques for 3D vector fields are applicable: \mathbf{s} consists of critical lines (i.e., for every critical point \mathbf{x}^* of the original vector field \mathbf{v} any point (\mathbf{x}^*, t) in the time-space domain will become a non-isolated critical point of \mathbf{s}), while \mathbf{p} does not have any critical points at all.

5.2. Feature Flow Fields

In the *feature flow field* (FFF) approach [TS03], a specially designed vector field in the 4D space-time domain captures parts of the topological information (critical points, periodic orbits, vortex axes) in its temporal evolution. Consider an arbitrary point \mathbf{x} known to be part of a feature in a (scalar, vector, or tensor) field. A feature flow field \mathbf{f} is a well-defined vector field at \mathbf{x} pointing into the direction where the feature moves to. Thus, starting a streamline integration of \mathbf{f} at \mathbf{x} yields a curve where all points on this curve are part of the same feature as \mathbf{x} .

Feature flow fields are commonly used with local features, which can be described by a local analysis of the underlying field and possibly its derivatives. Here, \mathbf{f} can usually be described by an explicit formula. In the 2D case the underlying vector field is given as follows:

$$\mathbf{v}(x, y, t) = \begin{pmatrix} u(x, y, t) \\ v(x, y, t) \end{pmatrix} \quad (10)$$

Using this description the direction of maximal change of the u and v -component of \mathbf{v} is given by the gradients $\text{grad}(u)$ and $\text{grad}(v)$. In the plane perpendicular to $\text{grad}(u)$ the u component remains constant in a first order approximation of \mathbf{v} . A similar statement can be made for v . Thus, the only direction in which u and v remain constant is the intersection of the perpendicular planes denoted by the cross product of $\text{grad}(u)$ and $\text{grad}(v)$:

$$\mathbf{f}(x, y, t) = \text{grad}(u) \times \text{grad}(v) = \begin{pmatrix} \det(\mathbf{v}_y, \mathbf{v}_t) \\ \det(\mathbf{v}_t, \mathbf{v}_x) \\ \det(\mathbf{v}_x, \mathbf{v}_y) \end{pmatrix} \quad (11)$$

In contrast to this, a FFF for a global feature can only be given in an implicit manner, since it can neither be decided locally whether a point belongs to a feature nor into which direction the feature evolves. Instead, the FFF approach has to be tightly coupled with a global feature detection strategy in order to assess global features.

Tracking features in time-dependent fields is one of the main applications of feature flow fields [TS03, TWHS04, TWHS05]. The temporal evolution of the features of \mathbf{v} is described by the streamlines of \mathbf{f} . In fact, tracking features over time is now carried out by tracing streamlines. The location of a feature at a certain time t_i can be obtained by intersecting the streamlines with the time plane t_i . Integrating the streamlines of FFF in forward direction does not necessarily mean to move forward in time. In general, those directions are unrelated and the direction in time may even change along the same streamline. Those changes are always related to special events, where multiple critical points merge, split up or vanish within the underlying vector field. Hence, FFF provides a tool to localize, characterize and classify bifurcations.

Besides tracking, FFF have been used for a variety of related problems. Those include topological simplification and comparison of vector fields based on critical point tracking [TRS03b], extraction of vortex core line defined as ridges/valleys of Galilean invariant quantities [SWH05], extraction and tracking of vortex core lines defined as centers of swirling motion [TSW*05], extraction of topological lines in tensor fields [ZP04, ZPP05], and identification of periodic phenomena from insufficiently time-resolved data sets measured using particle image velocimetry [DLBB07].

6. Local Methods

Features such as *edges* or *ridges* [Har83, EGM*94, Lin98] of images can be extracted by a type of methods that are *local* methods in the sense that they work on point-wise information, including derivatives. These methods carry over naturally from image data to scalar field data as they occur in scientific visualization problems. Height ridge extraction has been applied to pressure data by Miura and Kida [MK97] and to vorticity magnitude by Strawn et al. [SKA98], both times for finding vortex core lines. Ridge extraction from FTLE data was proposed by Shadden et al. [SLM05] for finding Lagrangian coherent structures.

For the visualization of vector fields such as velocity data, adaptations or generalizations of these methods can be used. Such techniques exist for the extraction of separation and reattachment lines [KHL99], vortex core lines [LDS90, SH95, BS95, MK97, RP98]. Some of these vortex core line methods involve additional physical quantities, in particular the pressure gradient [BS95, MK97], but the remaining ones, such as the classical methods by Levy et al. [LDS90] and by Sujudi and Haimes [SH95] are based solely on the velocity field and its derivatives.

Many of these structures can be expressed with a unifying formalism, called the *parallel vectors operator* (PVO) [PR99]. The PVO concept is not restricted to line-like features, but can be extended to surface-like features [TSW*05]. For the case of height ridges, simplified extraction methods were recently proposed for arbitrary di-

mensions, together with a new class of filters for the filtering of raw features [PS08].

In contrast to integration-based methods, local methods are comparably little affected by the unsteadiness of the velocity field. Therefore, most of the mentioned methods are directly applicable to unsteady flow. An exception is the recent extension of the vortex core line detector of Sujudi and Haimes to unsteady flow [WST07, FPH*08]. The reason for this was that the Sujudi and Haimes method can be re-interpreted as an operation on the acceleration field. If this is computed from a given unsteady velocity field, it requires a temporal derivative term, which is not needed in the steady case.

The general approach of defining and extracting features based on local criteria for the velocity field and its derivatives is a powerful concept, due to its mathematically rigorous formulations and the simple algorithms derived from them. At first glance, it may look wrong to describe global structures of a vector field by local operators. In fact, the different behavior of height ridges and watersheds in image data led to a lively dispute [KvD93, Ebe96] about the correctness of local vs. global methods. However, while in steady flow one of the most interesting topological structure, the separatrix, can be computed only using global methods, there is no reason to assume that this applies to unsteady flow as well. In a related context, Ginoux and Rossetto [GR06] showed that in 2D and 3D slow-fast autonomous dynamical systems, the *slow manifold* can be computed by finding zeros of curvature or torsion, resp., of the local trajectory. Finally, local methods can be combined with integration-based methods. An example is FTLE computation which leads to a scalar field and which has to be post-processed if sharp structures, such as height ridges, are needed.

Although the problem of detecting vortices usually is addressed using local methods as described above, they are methods that use a geometric approach. Sadarjoe and Post [SP99] suggest two methods detecting vortices in steady 2D flow fields detecting clusters of the osculating circle centers and streamlines with winding number 2π and relatively close start and end point. The latter method has been extended to 3D by Reinders et al. [RSVP02]. Petz et al. [PKPH09] propose a new criterion to characterize 2D vortex regions. In order to do so, they detect and cluster loops that intersect the underlying flow at a constant angle. Their algorithm is parameter-free and is not restricted to a certain type of geometry (e.g. star domains or convex domains).

Figure 7 shows visualizations of vortical flow using local (7(b)) and non-local (7(a)) detectors.

7. Stochastic and Multi-Field Approaches

Rarely the user is just interested in one aspect (i.e., one single feature type) of a flow field. It is more common to look at multiple features, features in combination with additional

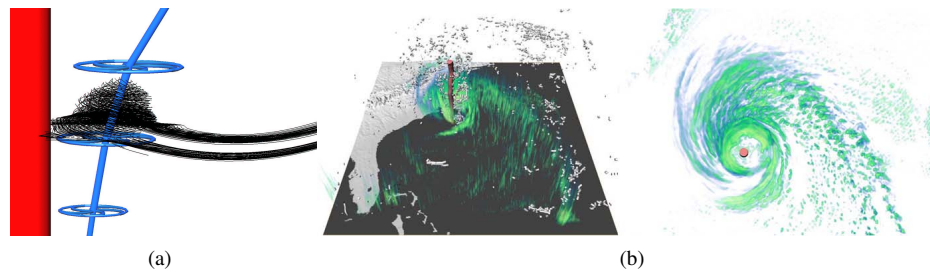


Figure 7: (a) Flow past a tapered cylinder visualized using a non-local vortex detector (image courtesy of Reinders et al. [RSVP02]); (b) Visualization of the core of swirling particle motion in the Hurricane Isabel data set (image courtesy of Weinkauff et al. [WST07]).

measures and/or multiple definitions of the same feature at once to get an understanding of the underlying field. Recently, a number of new approaches and methods have been introduced in order to take into account these requirements.

7.1. Interactive Visual Analysis

As the amount and complexity of data sets grows, automatic analysis methods are often not sufficient any more. In order to effectively cope with such data sets, interactive visual analysis (IVA) tries to balance human cognition and automatic analysis. The power of human perception and cognition is used to guide the analysis. The IVA approach provides an interactive discovery framework. It helps the user in getting insight, in understanding the data as well as complex, often hidden, correlations between certain data dimensions. The visual information-seeking mantra – *overview first, zoom in, details on demand* – as defined by Shneiderman [Shn96], summarizes the main idea. Coordinated multiple views [Rob07] are often used in this domain [MGJH08] as a proven concept. The main idea is to depict multiple dimensions using multiple views and to allow the user to interactively select (*brush*) a subset of data in one view and all corresponding data items in all linked views will be highlighted as well [MW95, DGH03]. One of the first examples of linking and brushing with different visualization approaches in different views is a system called WEAVE [GRW*00], which was used to interactively analyze and visualize simulated data of a human heart application using focus+context visualization [Hau03]. IVA is used in many domains [KMSZ06]. In the following, however, we will focus on engineering and scientific applications.

Doleisch et al. have developed a system called SimVis for interactive feature specification and localization in 3D flow data [Dol07, DMG*05, DMH04, LGD*05]. They use simple 2D linked views, such as scatter plots or histograms, for the specification of flow features. Linked 3D views provide spatial information and advanced flow visualization techniques. Complex features can be described by composite brushing.

The feature definitions are expressed in an XML-based feature definition language and are persistent across analysis sessions. The SimVis system has been used to analyze flows from numerous applications, such as flow through a catalytic converter, flow around a car, cooling jacket flows, etc.

Another approach deals with the parametrization of pathlines in order to understand flow. The main idea is to compute various attributes from pathlines in order to understand the flow itself. Shi et al. [STH*07] compute scalar and time series attributes of pathlines, such as: winding angle, Lyapunov exponent, direction vector, etc., and then use coordinated multiple views in order to understand the flow behavior.

Figure 8(a) shows their interface while analyzing a data set.

Bürger et al. [BMDH07] have computed several local feature detectors of the same flow and used IVA to compare them. In addition other flow attributes (such as pressure, ...) were taken into account as well. In this way it can be intuitively decided which automatic method gives more accurate results in certain areas or time intervals. Such an approach enhances the credibility and combines the advantages of several detectors in an interactive visual analysis system.

IVA is not a competitor or an alternative to the detectors described before. It has to be used in parallel. It offers great potential in the exploratory phase, during hypothesis generation. The flow segmentation is not an isolated process, it is part of a larger work flow. Domain experts analyzing the flow have to choose detectors, and IVA can help in deciding if detectors are applicable, if a detector functions in particular case. If sampling is too coarse maybe some detectors do not function, for example. Domain experts have to evaluate multiple detectors. Engineers, for example, compute a vortex detector first, and then check if this is an area of low pressure, as well. The analysis can be refined for areas where this holds, and can be skipped for other areas. IVA, with its multiple views, intuitive interfaces and quick selection possibilities, offers a useful tool for such complex task. IVA can also help to improve robustness of detectors. A filtering step is almost always necessary after a detector is evaluated. If

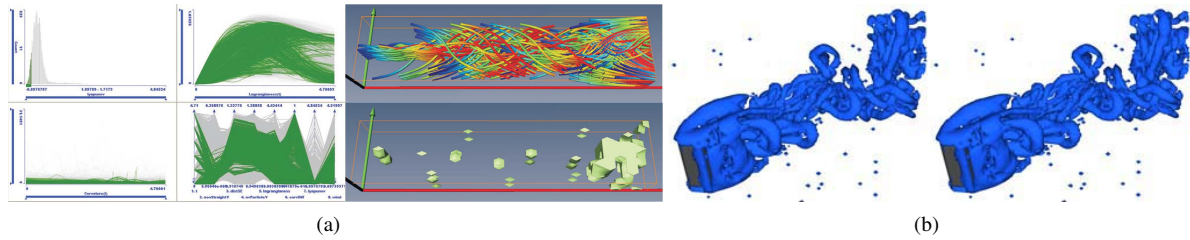


Figure 8: (a) Pathlines with small Lyapunov exponents in a flow behind a circular cylinder. The region to display is selected in the histogram (upper left window) the corresponding pathlines (upper right display) and their seeding points (lower right display) are displayed (image courtesy of Shi et al. [STH*07]); (b) Comparison of the visualization of a flow around a cuboid using the standard λ_2 -criterion (left) and local statistical complexity (right) (image courtesy of Jänicke et al. [JBTS08]).

we allow smooth brushing [DH01], a method which allows non-strict brush boundaries, local characteristics of detectors can be examined much easier. Hauser and Mlejnek [HM03] showed how similar approach can be efficiently applied to isosurfaces in the analysis of flows in a catalytic converter.

IVA is certainly not another flow segmentation method, but rather integrative approach which helps domain experts to understand detectors and flow behavior. It has a great potential and is increasingly used in order to efficiently combine various approaches and integrate them in the engineers' work flow.

7.2. Fuzzy Feature Detectors

While IVA handles multi-field structures (induced by multiple features, multiple definition of features and/or additional quantities) inducing multiple views and linking+brushing, other attempts have been made to address problems related to feature extraction and visualization in fashion that corresponds more to the classical methods in flow visualization with respect to their outputs.

One of the drawbacks of feature extracting methods is that the user has to be aware of the type of feature which should be extracted. Additionally, the feature one is looking for may not be defined unanimously (e.g. vortices). In order to address this problem, Jänicke et al. [JBTS08] recently presented an improvement of the algorithm of Jänicke et al. [JWSK07] for an automatic extraction and visualization of regions of interest in 3D unsteady multi-flow. The authors detect space-time points that have high probability to develop into unlikely in future using a statistics-based algorithm. As a measure for the unexpectedness of the value at a point they propose *local statistical complexity*, which is, roughly speaking, the amount of information needed to predict the future of a space-time point.

Figure 8(b) shows a visualization of a flow around a cuboid obtained by this method.

Salzbrunn and Scheuermann suggest the use of *streamline predicates* in order to combine flow topology with fea-

ture extraction [SS07]. The main idea is to decompose the domain into disjoint regions with coherent streamline behavior like flow topology does, adding other distinctions than asymptotic behavior. This addresses, e.g., the problem that some features (e.g. vortices) can be split up by usual flow topology. Mathematically speaking, streamline predicates are Boolean maps on the set of all streamlines with disjoint support. Flow topology is then a special case of segmentation gained through streamline predicates, called *flow structure*. Classical feature detectors can be used to refine flow topology using streamline predicates.

The same ideas are applied to unsteady flow by Salzbrunn et al. [SGSM08]. In analogy to the steady case the authors introduce the notation of *pathline predicates*. Additionally, the authors present a pathline placement strategy in order to combine the structural overview provided by the partition gained by means of pathline predicates with the dynamical insight into the flow provided by tracing single particles.

In engineering context feature models with parameters are often used. The quantification of these parameters is obviously an important task. Ebling et al. [EWGS07] point out that topology-based methods are not capable of doing this. They show, e.g., that for an arbitrary vector field the topological skeleton of the normalized field is the same as the skeleton of the original field. Another drawback of topological methods in this context is that superposing features may not be detected correctly. The authors suggest therefore the use of vector masks and pattern matching. This approach emphasizes the interpretation of a vector field as the superposition of many (simpler) fields.

8. Discussion and Conclusions

This paper describes the current state of the art in topology-based flow visualization of unsteady vector fields. To this date, the solutions for unsteady flow remain still incomplete, compared to the level of proficiency achieved for steady flow. Incremental extensions of methods for steady flow are proven to be not able to capture the true flow behavior. Therefore new approaches and methods have been

introduced, including both new theoretical frameworks and methodical novelties. Many of the new approaches seem to overlap to some extent. This hints to that a unified framework for treating unsteady flow with topology-based methods could be found. Future work in this direction seems promising.

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