Localized Flow, Particle Tracing, and Topological Separation Analysis for Flow Visualization

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The present thesis focuses on the visualization of vector fields with an emphasis on flow fields. In connection with a DFG project, close collaboration and discussions with fluid dynamicists raised new questions concerning the detection and depiction of special features in flows.

The contributions of the thesis in this context are the following: First, we present and apply a method to extract the contribution of a subregion of a flow to the global flow. To isolate this contribution we decompose the flow in the subregion into a potential flow that is induced by the original flow on the boundary and a localized flow. Since the potential flow is free of both divergence and rotation the localized flow retains the original features and captures the region-specific flow that contains the local contribution of the considered subregion to the global flow. We discuss the application of some widely used feature extraction methods on the localized flow and describe applications like reverse-flow detection using the potential flow. Furthermore, an extension to time-dependent fields is given.

Next, to complement animations that provide only transient impressions of momentary flow, two approaches to visualize time varying fields with fixed geometry are introduced. We show how bundles of pathlines running at different times through one point in space yield an insightful visualization of flow structure. As second approach, we use a simple measurement of local changes of a field over time to determine regions with strong changes.

Concerning the interaction between wall shear stress and three-dimensional flows, we propose a method for the extraction of separation manifolds originating from separation lines. We address the problem by investigating features in flow cross sections around separation lines. We use the topological signature of the separation in these sections, in particular the presence of saddle points and their separatrices, as a guide to initiate the construction of the separation manifolds.

Further investigating wall shear stress and three-dimensional flows, we present a method to visualize vortices that originate from bounding walls of three-dimensional time-dependent flows. These vortices can be detected using their footprint on the boundary, which consists of critical points in the wall shear stress vector field. In order to follow these critical points affected regions of the surface are parameterized. Thus, an existing singularity tracking algorithm devised for planar settings can be applied. The trajectories of the singularities are used as a basis for seeding particles. This leads to a generalized concept of streaklines which visualize the particles that are ejected from the wall.

Finally, we apply the concepts of finite-time Lyapunov exponents to enable the analysis of steady and unsteady flows in the immediate vicinity of the boundaries of flow-embedded objects by limiting Lagrangian analysis to surfaces closely neighboring these boundaries. To this purpose, we present an approach to approximate FTLE fields over such surfaces. Furthermore, we achieve an effective depiction of boundary-related flow structures such as separation and attachment over object boundaries and specific insight into the surrounding flow using several specifically chosen visualization techniques.