Trajectory Visualising and Convolution Control and Application for Vortex Detection

Bilal Alsallakh
Institute of Computer Graphics and Algorithms
Vienna University of Technolgy
Vienna / Austria

Abstract

We present a new analysis technique for pathlines in 3D simulation data by visualizing the distribution of the scalars along pathlines in a separate 2D view. The presented visualization is applicable for vortex detection and for understanding the development of scalar properties of particles during their traversal through the simulation domain. Furthermore the presented 2D view can be coupled with classical Lagrangian vortex detection criteria, which enables easier control for the detector parameters. Also we can benefit from linking and brushing techniques of interactive visual analysis and control the rendering of these trajectories (i.e., stream- and pathlines).

Keywords: *trajectory visualization, interactive visual analysis of flow simulation data*

1 Introduction

Streamlines and pathlines in three-dimensional flow simulation data are essential structures that have been used extensively to study and understand the flow. Many visualization techniques have been devised that intend to help the engineer analyses these trajectories in the 3D volume (see Figure 2.a for an example). However, when using three dimensional visualization alone much information about the trajectories is lost due to problems of occlusion and the difficulties of understanding the geometry of three dimensional lines after projection to 2D-images.

Streamlines and pathlines have been suggested to achieve delocalization for the problem of vortex detection. The Lagrangian approach to understanding the behaviour of fluids focuses on the development of particles as they move through the fluid. This is in contrast to the Eulerian perspective where we focus on the change of flow properties at one specific location. In the last decade much research has focused on improving the understanding of the Lagrangian point of view.

To provide an interactive user control over the delocalization of vortex detection, first the streamlines should be visualized intuitively, giving insight into the development of the local volume properties along these streamlines, and second, the user selection of parameters should be intuitive and well defined.

Inspired by information visualization techniques we present a 2D view that can complete the information lost in 3D renderings. Here we investigate an approach to visualize the pathlines in a separate view beside the 3D view of the volume and enable the desired problem-specific user control. To visualize the distribution of scalars along trajectories (e.g. temperature, velocity or vorticity magnitude) we draw the trajectories as straight lines discarding most of the geometric information of the pathlines.

Using the presented visualization technique we get access to non-local features of the flow.

In the next section, we present the motivation for the work and present criterion devised for vortex detection. The third section presents the visualization concept and user interaction, and the fourth section shows how the implemented can be used to steer the vortex detection process and the rendering of the results back in 3D. In the fifth section we present evaluation results and then we conclude the work.

2 Motivation and Related Work

One important problem in flow analysis is the detection of vortices in the flow, which represent spinning or spiral flow (Fig.1). These vortices can be observed in many natural phenomena such as Hurricane and Tornado formation, and play a major role in aerodynamics, hydrodynamics, and many other fields.

Understanding the relations of the fluid properties, their structures, formation and effects is essential in studying these phenomena. Better visualization and investigation of these properties allow better understanding of the information in fluid simulation datasets in general. From the engineering viewpoint, improving turbulence models is important for high Reynolds number flow simulations since and will improve the accuracy of simulation results. Also, detecting flow vortex structures and understanding their interrelations within the simulation dataset can help the engineer improve the design of his product since vortex structures have critical impact on material transport, mixing, wear and many other application central properties of the flow. Therefore, vortices are considered as one of the most important coherent structures in turbulence. Many local physical quantities where suggested as a measure for the presence of vortices, such as:

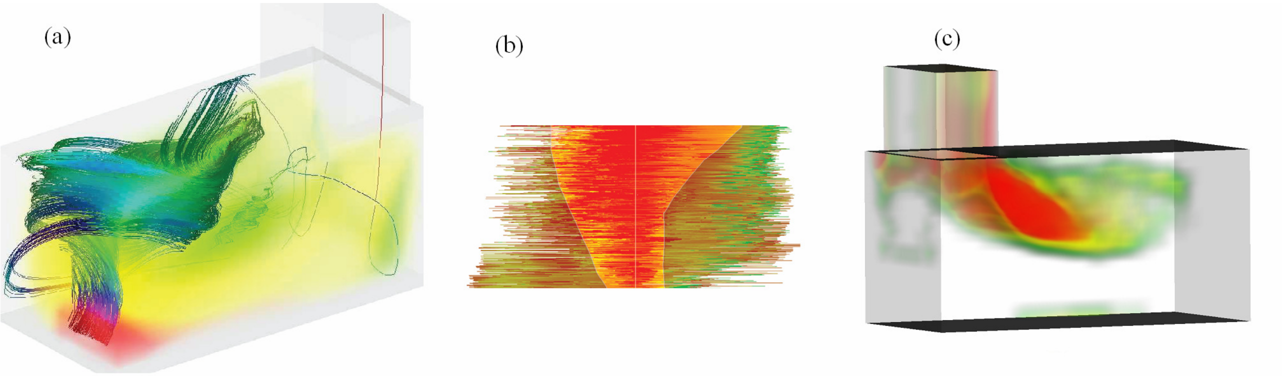

Figure 1: (a) the pathlines in 3D, high clutter (image courtesy of M. ILCÌK [BMI07]. (b) pathlines visualization and manipulation in 2D. (c) the desired insight into detector responses made accessible by the view in (b).

- Hunt's Q criterion
- λ_2 introduced by Jeong and Hussain
- Kinematic Vorticity Number
- Chong's criterion

However the intrinsic locality in these criteria makes them suffer from considerable presence of false positives. In [FAG08] the use of a more global approach for vortex detection to avoid this limitation is investigated. The local criteria are evaluated over path-lines passing through the cells, which provides more global information to decide if the current cell belongs to a vortex or not.

A pathline can be formulated as:

$$p(t+\Delta t) = p(t) + \int_{t}^{t+\Delta t} \mathbf{u}(p(t),t).dt$$

where $p(t)$ is the position of the particle at time t, and $\mathbf{u}(p(t),t)$ is the velocity of the particle at position $p(t)$ at time t.

The pathlines can be computed using forward and backward integration at each cell, and the delocalized detector response at a cell is computed by using the responses along its pathline. This means that the detector response at a cell depends not only on the local properties evaluated at this cell, but rather, it incorporates information from other cells. This enables distinguishing actual vortices with cells having high response values from outliers that have high responses only locally. For this approach to work, two issues should be handled carefully:

The range of integration: the pathlines can traverse arbitrarily through the volume having arbitrary lengths. For delocalizing the vortex response at a cell, only a specific range along this path-line would be useful. This range would differ depending on the size of the candidate vortices, and the location of the cell relative to the closest vortex.

The computed response: although we intend to incorporate delocalized information in the computed response, but still, local information should receive higher importance to avoid getting high responses in unexpected regions. Thus more weight should be given to the localized response and this can be achieved by multiplying the responses with a suitable kernel (Gaussian or tent function). Furthermore, the responses should be combined in a way which tolerates the presence of outliers.

As we can see above, there are many parameters to be adjusted for the vortex detection process, of which the integration boundaries is to be assigned for each path-line (and hence per simulation cell). Information visualization provides a rich environment for this purpose, enabling performing semi-automatic and interactive detection, and gaining insight into the detection results, by means of controlling the above mentioned parameters in a separate view.

We have implemented the work as a plug-in view in the SimVis visualization framework, which provides standard InfoVis views, and an extendible API to create new views, and an elaborate mechanism to link views and define fuzzy selection. More information about SimVis can be found in [KDGH04]. Furthermore, we kept the rendering part of the view independent of vortex-specific features or constraints which makes the view applicable to other domains that need visual analysis of pathlines in 3D volumes.

3 Line View

As we can see in Fig. 1-a, rendering the pathlines directly in the 3D volume will lead to a hardly avoidable clutter. Therefore we decided to visualize the lines in a separate 2D view and enable manipulation and adjustment of the required parameters for the application in hand (Fig. 1-b and Fig. 3).

The path-lines are visualized in the 2D view as straight lines, which gives more space to visually convey information about them and enable easier selection and brushing operations. The spatial information for these lines can still be conveyed by means of inter-view selection, which is supported by the view linking feature in the SimVis Framework so that the selected lines in the 2D view can be back projected in 3D. Fig.

1-c shows the selection results rendered back in the 3D volume (here we visualize only the volume cell from which the selected pathlines originate). As can be seen in this figure, there is much less clutter, and better insight.

For the purpose of vortex analysis, our main interest is to observe how the vortex classifier response is distributed along the pathlines, and using this visual information, choose the integration range for each line.

3.1. The visualization concept

Each path-line is visualized simply by placing its segments successively on a straight horizontal line, and assigning each segment a color based on its cell vortex response. The resulting horizontal lines are evenly distributed along the vertical access to fill the available viewing space.

One can think of this visualization, as if we flatten the pathlines and then draw them in the plane, stacked on top of each other, and colored according to the vortex response along each line (Fig 2). The lines are aligned horizontally, so that they start together from the same coordinate, and grow in both directions.

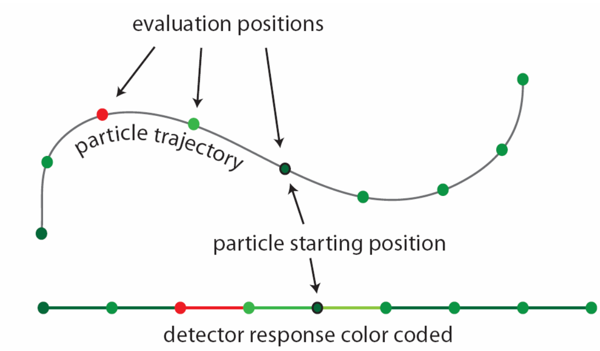

Fig. 2: flattening the path-line. The 3D segments are mapped to 1D segments of equal length (Image courtesy of R. Fuchs [FAG08])

Each pathline segment is restricted to one cell in the 3D volume. Hence, various volume local properties can be mapped to the segments. In the line view, the segment is assigned a color based on the value of a user defined volume property at the corresponding cell.

Fig. 3 shows a sample line view for the streamlines depicted in Fig1. The starting position of each pathline is mapped to the midline of the view, and the pathlines can grow in both directions (backwards and forwards). The exact screen location of the midline is decided based on how long the pathlines extend in both sides, and the available screen width.

Color assignment: The colors are assigned to the segments drawn via a transfer function which maps the local feature values to color and opacity.

Certain lines can be assigned smaller opacities depending on an external input which can weigh the importance of the cells based on a selection from another view. This enables quick elimination of unwanted lines, based on information from other task-specific views.

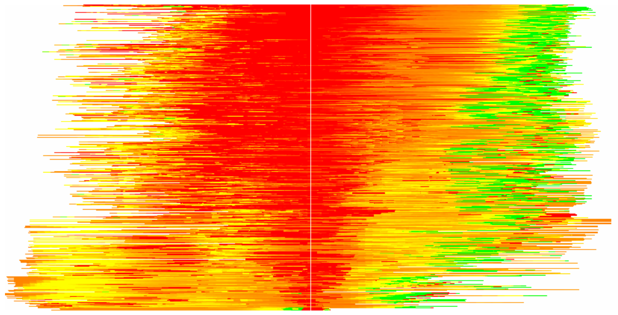

Fig. 3: The 2D Line View: The 3D pathlines are visualized as parallel straight lines in 2D with the color coding a selected volume feature.

Standard image processing techniques can be applied to enable further exploration and analysis in the view. In particular we found histogram operations useful.

Line Fusion: line fusion is necessary when there are fewer pixels available in height than lines. If that is the case, we divide the lines into as many groups as there are pixels available. In case the division has a non zero modulo, the remaining lines are assigned so that the groups having one more line are evenly distributed

Instead of computing and then combining the visual properties for individual lines, we employ post-classification, by first combining the values along the group lines, and then assigning the appropriate visual properties to the resulting line by means of the transfer function. To combine a group of lines into one line, we first align the lines so that the segments corresponding to the cells, from which the lines originate, start from the same location (the midline of the view). Then we advance a vertical scan-line along the group lines in each direction starting from the midline. Each time am advancement is made to the closest start of a segment in one of the group pathlines, and a new segment is added to the output lines of length equal the advancement, as explained in Fig.4. The output segment is assigned a response equal to the combination of the values corresponding to segments lying in the advancement interval in the group pathlines.

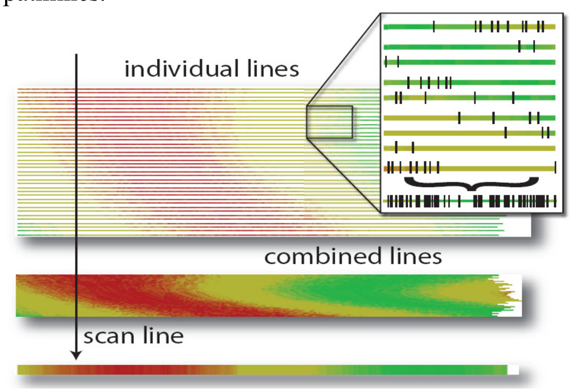

Fig. 4: Line fusions: A set of lines are visualized as one line, due to limited screen space, by combining their values (Image courtesy of R. Fuchs [FAG08])

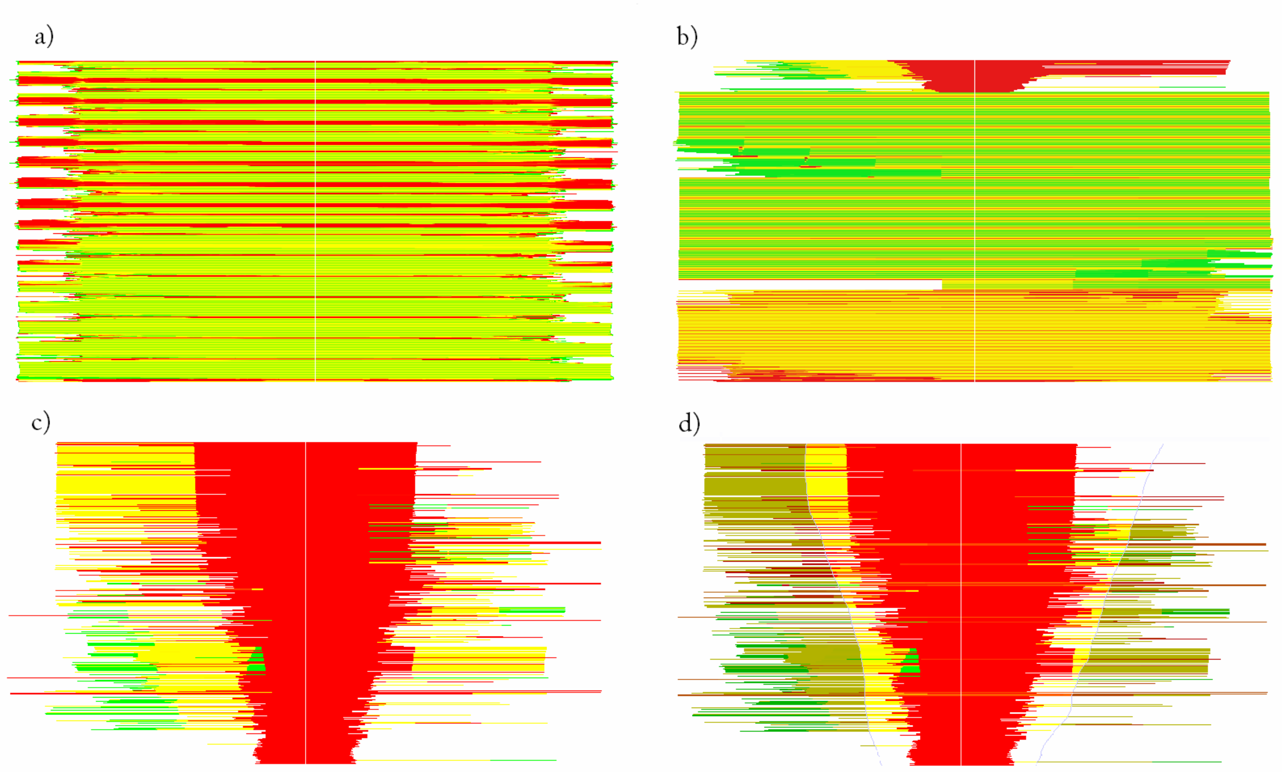

Fig.5: typical user interaction steps. a) the unsorted lines. b) sorting the lines based on their response around the midline. The red region reflects higher responses. c) filtering the lines with small keys. d) perofming the selection.

As combination function, the user can choose between minimum, maximum and average, depending on the application.

3.2. User Interaction

The view provides basic interactivity which can be customized to enables task specific manipulation. An interaction session starts by the user choosing the dataset for the pathlines, and that of the volume these lines are computed into. Then the desired time step and the volume property to map onto the pathlines can be specified. The view intends both to give insight into the pathlines and the distribution of the values along them, and equally importantly to enable selection of candidate pathlines that bear a specific meaning (for example originate from cells belonging to a vortex). The results can be best viewed in a 3D view of the volume.

Zooming: zooming into the data is straightforward. It is achieved by defining the horizontal and vertical bounds for the region that should be displayed. While line fusion helps giving an overview of the lines and the candidate regions and structures, zooming in is necessary for avoiding the loss information caused by the fusion, and observing fine details.

Sorting: The lines are initially viewed without any specific order (Fig5-a). While our view intends to discard geometric and topological information in favour of higher insight in the distribution of the values, it is still meaningful to define an ordering on the lines. The usefulness of such ordering and how to perform it is clearly application-specific. For example, one can define the ordering which makes lines having higher values appear first, and hence visually form a group. This make selection based one some criterion much easier by assigning higher sorting keys to the lines which fulfil the criterion strongly, and hence getting them appearing grouped at the top instead of having them scattered in the view. Furthermore, for keys which are correlated with the values along the pathlines, sorting minimizes the loss of information caused by fusion, since the variance of the values combined is rather small.

Filtering: The lines can be filtered based on the sorting key, so that only the lines having leys in a specified range are retained (Fig5-c). This enables quick exclusion of many unnecessary lines (and hence, cells) which would otherwise cause clutter both in the 2D and 3D view, slow down the performance and increase the loss by fusion.

Selection: After having the lines sorted and filtered, selection is simplified. Selection aims at assigning a membership value in the range [0, 1] for each pathline which gives how strong this pathline belongs to the selection output. This membership function, and hence the required user interaction scenario depends strongly on the application in hand.

(Fig5-d) shows a sample selection method, which was devised for the task of vortex detection in [FAG08].

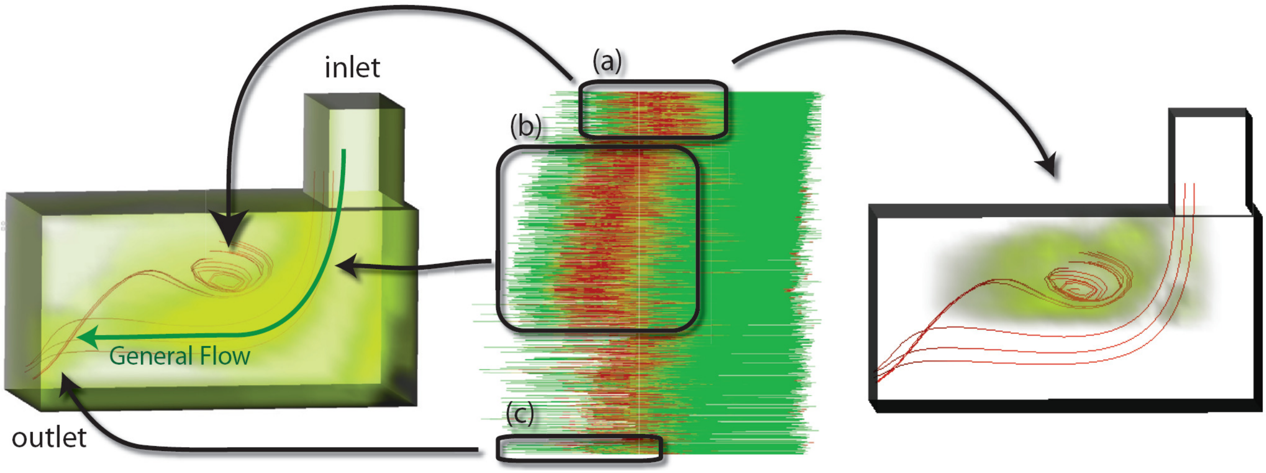

Fig.6: Using the implemented line view to explore the vortices (Image courtesy of R. Fuchs [FAG08])

4 Application in vortex detection

As have been explained in section 2, the motivation for the work, was to visual the pathlines and enable user interaction for the purpose of vortex detection, were pathlines are used to introduce delocalization by integrating the local vortex responses along the pathlines, but as we discussed, two issues need to be add the addressed for this approach to give good results:

Integration range: Only a sub-range along each pathline should contribute to the overall integral response. One end of this range defines the limit for forward integration, and the other end defines the limit for backward integration. This means that the selection range always contains the midline. Enabling this range selection is straightforward in our line as explained in (Fig5-d). With the mouse, the user can interactively decide the left and right end for each pathline, based on the color distribution. We visually communicate the selection by assigning weaker brightness to regions out of the selection.

The declocalized response: for the weighted local responses discussed in section 2, which are inside the selection range two combination methods have been investigated in [FAG08]

- Thresholding and summation: we subtract the weighted responses from a user defined threshold, and sum up the resulting values. However, significant outliers could still affect the overall response, which could be partly alleviated by trimming the summed values by a limit.
- Valid range width: we subtract the responses along the path-line from a user defined threshold, and compute the width of the range around the starting cell which has positive values. To deal with outliers, we tolerate a small gap inside the range having negative values (weighted response lower than the threshold) using a user-defined gap tolerance. This method led to more robust detector which could tolerate noise. But the degree of response does not correspond directly to the higher vortex probability, though it is correlated with it.

For sorting, we use one of the above mentioned combination methods with infinite selection ends to compute the sorting key.

After the lines are sorted and possibly filtered, selection can be performed as explained above enabling intuitive interactive visual analysis, where the structures present in the view which can possibly represent actually vortices can be selected. The selection assigns for each cell, the normalized response value its pathline receives, these values can be visualized back in 3D, which helps understanding the flow. Also, using this selection mechanism, candidate vortices can be isolated and analysed separately.

5 Results

Here we present testing results using the connect dataset (Fig. 7), where the inlet of the volume is left. The pathlines are generated using forward and backward integration, and visualised using the line view in Fig.5-a. The mid-line shows the local responses (responses at the starting cell) for each line.

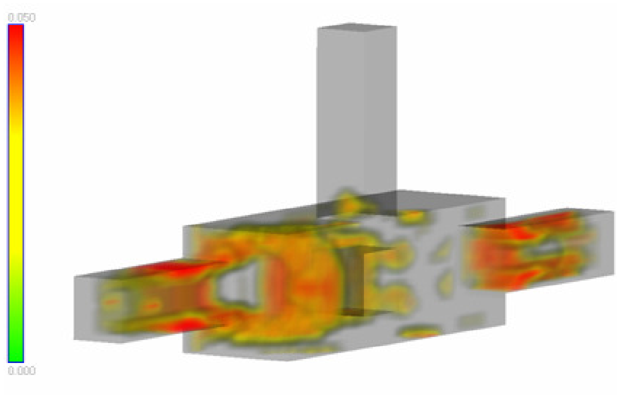

Fig. 6: The connect dataset, and the detected vortices

After manipulation and selection (Fig.5-d), the selection results are visualized back in Fig. 6. As we can see the delocalization has helps doing decent separation between the vortices.

6 Conclusion

In this work, we introduced an info-vis view to visualise path-lines and use intuitive methods to manipulate them with simple operations like zooming, sorting, filtering and selection. An application in vortex detection has been presented, and the same idea can be employed in other application, where complex sub-structures in a view need to be analysed. In the current implementation, the manipulation operations where implemented for the vortex detection problem. A more elaborate set of operations, and enabling user definition of sorting keys and selection criteria will make the view more general and seamlessly applicable for similar problems.

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