Flow Visualization and Analysis: From Geometry to Physics

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Outline

- Problem Definition

- Lagrangian Accumulation Framework (done)

- TAC and Multi-TAC based Framework (on-going)

- Future Work & Questions
Why Vector Fields are Important?
Vector Fields in Engineering and Science

**Automotive design** [Chen et al. TVCG07, TVCG08]

**Weather study** [Bhatia and Chen et al. TVCG11]

**Oil spill trajectories** [Tao et al. EMI10]

**Aerodynamics around missiles** [Kelly et al. Vis06]
What are we looking for from vector fields? 

- sufficient spatial coverage
- salient flow patterns (reduced cluttering)
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- salient flow patterns (reduced cluttering)

An abstract representation is strongly need!
Related Work - Vector Field Topology

• Goal
  Obtaining a compact representation of a vector

• Pros
  Providing a holistic understanding of the flow in a more semantic level

• Cons
  Challenges in unsteady flow
  Pure geometry, no physical info

Entity Connection Graph [Chen et al. TVCG07]

[Chen et al. TVCG07, TVCG08, TVCG11a; Szymaczak et al. TVCG12, TVCG13; Haller 2001]
Related Work – Geometric-based Flow Visualization

• Goal
  Extracting representative geometric objects: streamlines, pathlines, surfaces etc.

• Pros
  Data compressed
  Intuitive visualization

• Cons
  May loose some important features

Salzbrunn et al. TVCG06, 2008; Shi et al. TVCG08; Weinkauf et al. TVCG10, TVCG12; McLoughlin et al. TVCG13.
Related Work – Attributes-based Flow Visualization

• Goal
  Extracting local/global attributes of integral curves

• Pros
  information visualization

• Cons
  Additional efforts needed to interpret the result
  Lack of details

Pobitzer et al. PacificVis12, 2008; Guo et al. PacificVis14; Shi et al. CGA08, TopoInVis09.
Motivation
Physical Features

• Flow separation
  • FTLE/LCS
• Vortex
  • $Q$-criterion and $\lambda_2$-criterion

• Dissipation and Diffusion

• Dispersion
  • Dispersive mass transfer
  • Atmospheric dispersion

Is it possible to make a theoretical model to describe the behavior of a turbulent flow — in particular, its internal structures? (unsolved problem in Physics)
Problem Definition

• A Physics-based Flow Exploration Framework
  • Apply to different categories of Physical feature
  • Achieve a level-of-detail flow exploration

The illustration of the gap between geometrics representation and physical interpretation. (a) A number of pathlines with homogeneous behaviors. (b) The time activity curves of the physical attribute $Q$. (c) Accumulated $Q$ field values of each corresponding pathlines in (a).
Time Activity Curve (TAC)

• Definition

Given an integral curve $C_{x,t}$ seeded at $(x, t)$, computing a local attribute $A$ along the curve gives rise to a time series data, which we refer as a Time Activity Curve (TAC) of $C_{x,t}$ on the attribute $A$.

$$\Gamma_{A,C}[i] = A(C(x, t_i), t_i) | i = 1, 2 \ldots n$$

(a) A pathline. (b) TAC of the pathline on physical attribute $Q$. 

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Expected Contributions

- A Lagrangian accumulation framework (done)
  - Derived attribute fields
  - Properties study
  - Integral seeding
  - Flow segmentation
  - Discontinuity study

- TAC and Multi-TAC (on-going)
  - Event detection
  - Hierarchical clustering based on TAC
  - Stable set analysis
  - Correlation study
Outline

- Problem Definition
- Lagrangian Accumulation Framework (done)
  - Definition
  - Properties
  - Exploration framework
  - Applications
- TAC and Multi-TAC based Framework (on-going)
- Future Work
L.A. - Definition

Consider an integral curve \( C \), starting from a given point \((x, t)\), the Lagrangian accumulation can be formulated as:

\[
A_g(x, t) = \int_{T_1}^{T_2} k(\tau)A_I(C_{x,t}(\tau), \tau) d\tau
\]

Similarly, the accumulation can also be done within a range along the integral curves with a specified length

\[
A_g(x, t) = \int_{s_1}^{s_2} k(s)A_I(C_{x,t}(s), s) ds
\]

\( A \) Field: a derived scalar field obtained from the above convolution.
L.A. - Definition

An example of the Rotation field - $\Phi$

$$\Phi = \sum_{i=0}^{N} d\theta_i \quad \nabla \Phi = \left( \frac{\partial \Phi}{\partial x'}, \frac{\partial \Phi}{\partial y'}, \frac{\partial \Phi}{\partial z} \right)$$

Assuming the integral curve $C$ is represented by $N$ integration points $P_i$, $d\theta_i$ represents the angle difference between two consecutive line segments on an integral curve. We use box-filter for all the examples, therefore, the kernel function $k_i = 1$. 
An Attribute Field

The result of the double gyre flow with $T = 10$. [Zhang et al. VDA2016].
L.A. – Exploration Framework

[Flow map estimation] → [Accumulate attributes] → [Compute Gradient]

[Visualize $\phi, \nabla\phi$] → [Integral curve filtering, seeding] → [Detect Discontinuity] → [Flow Segmentation]

[Visualization and data exploration]

[Zhang et al. VDA2016].
L.A. – Application

• Discontinuity Study

Discontinuity detection using the Canny edge detector with different combinations of parameters [Zhang et al. TopoInVis2015].
L.A. – Application

• Flow Segmentation

Segmentation and estimated boundaries of a 3D steady flow behind cylinder. [Zhang et al. JofVis2016].
Where, when and how long the events of interest occur?

- Limitation of Lagrangian Accumulation
Outline

- Problem Definition
- Lagrangian Accumulation Framework (done)
- TAC and Multi-TAC based Framework (on-going)
  - Definition
  - TAC decomposition
  - A Hierarchical Clustering Framework
  - Applications
- Future Work
TAC and Multi-TAC

• Single TAC
• Event Definition

\[ \forall k \in (i, j), E = \begin{cases} 
    \text{Increasing} & \Gamma[k] > \Gamma[k - 1] \\
    \text{Stable} & \Gamma[k] = \Gamma[k - 1] \\
    \text{Decreasing} & \Gamma[k] < \Gamma[k - 1] 
\end{cases} \]

An example of an event (b) detected by a given TAC (a).
TAC and Multi-TAC

• Multi-TAC
• TAC Decomposition

An example of multi-TAC and its decomposition.
TAC and Multi-TAC

• Hierarchical Clustering based on TAC

An illustration of agglomerative hierarchical clustering (AHC) algorithm.

AHC result of Double Gyre flow based on TAC of curl field. Five clusters are displayed. (a) TAC-clusters. (b) Pathline clusters.
TAC and Multi-TAC - Applications

• Correlation Study

The scatter plot matrix of different attribute fields of the Double Gyre flow.
TAC and Multi-TAC – Future Work

- TAC related similarity metric
  - Study classic Euclidean distance, Manhattan distance and Pearson correlation
  - Propose a new TAC-based metric
  - Define distance of multi-TAC

- Stable set analysis
  - Study geometrically neighboring particles with high similarity to a given TAC of interest
  - Reveal relations between geometrics attributes and physical attributes
TAC and Multi-TAC – Future Work

▪ An extended descriptor
  ▪ Introduce some statistical metrics

▪ New applications
  ▪ Vortices related attributes study under the new framework
  ▪ Time-varying multi-fields correlation study based on TAC
Questions

- The motivation of our work is to bridge the gap between the geometric representation and the physical interpretation of the flow behaviors that are of interest to the experts. Is the motivation strong enough for the proposed dissertation work?
- We try to use the accumulation framework and TAC-based framework to provide two levels of flow visualization (global v.s. detailed information). In the perspective view of visualization, does the proposed work has potential impact to the visualization community?
- TAC-based similarity metric encoding events(trend) difference?
- What Physical features people care about?
Thank you!