Recent Advancements of Feature-based Flow Visualization and Analysis

Jun Tao, Hanqi Guo, Bei Wang, Christoph Garth, and Tino Weinkauf

TITLE

Recent Advancements of Feature-based Flow Visualization and Analysis.

DURATION

The tutorial is full-day, including 250 miniutes presentation, 50 minutes discussion, and 130 miniutes coffee break and lunch time.

SCHEDULE

Introduction	All	10 minutes
Talk1	Jun Tao	50 minutes
Talk2	Tino Weinkauf	50 minutes
Break	———	20 minutes
Talk3	Bei Wang	50 minutes
Lunch	———	90 minutes
Talk4	Christoph Garth	50 minutes
Talk5	Hanqi Guo	50 minutes
Break	———	20 minutes
Panel discussion	All	50 minutes
Closing remarks	All	10 minutes

ORGANIZER

Christoph Garth	University of Kaiserslautern
Hanqi Guo	Argonne National Laboratory
Jun Tao	University of Notre Dame
Bei Wang	University of Utah
Tino Weinkauf	KTH Stockholm

ABSTRACT

Flow visualization has been a central topic in scientific visualization for many years, which can be explained by the ubiquity of vector fields in various kinds of scientific, engineering, medical researches. In all these domains, with today's ever-growing computation power, numerical simulations produce large, time-varying and highly complex vector fields. Preserving the rich information in these large and complex vector fields and presenting concise visualizations for clarity are two desired goals, but they are often conflicting. Striking a balance between them is challenging, which requires us to better distinguish the features from the contexts. Understanding and extracting features become critical to obtain insights from the vector fields with growing sizes and complexities.

In this tutorial, we cover different topics centered at the feature-based flow visualization and analysis: (a) interactive techniques that allow users to discover their features of interest; (b) spatio-temporal flow analysis that considers n-dimensional unsteady flows as (n+1)-dimensional steady flows; (c) feature extraction, tracking and simplification with robustness that captures structural stability of the data; (d) vector field techniques for large-scale time-varying data, especially the parallel algorithms and in-situ techniques; and (f) theories and scalability issues in ensemble and uncertain flow. This tutorial aims at providing information of the state-of-the-art techniques for feature-based flow visualization in different aspects, including interactive exploration, large-scale time-varying data, topological robustness and ensemble data.

LEVEL

Intermediate/Advanced.

PREREQUISITE

A general understanding of flow fields and flow visualization, including basic concepts and techniques, such as different kinds of field lines, critical points, and particle tracing, etc.

DESCRIPTION

The description and outline of each topic are presented as the followings:

Expressive Flow Field Exploration
Jun Tao

Abstract A major task of visualizing steady flow fields is to allow users perceive the flow patterns and locate features of interest. Traditional flow visualization approaches, such as seed placement and streamline selection, generate an appropriate set of streamlines to describe steady flow fields. However, only limited capabilities are provided to meet specific needs from different users, especially at the streamline segment level. In this talk, we will start from an automatic streamline and viewpoint selection framework, and then introduce three interactive exploration approaches. We demonstrate that the transition from the automatic approaches to the interactive ones provides more flexibility that allows users to specify, identify and observe their interested patterns/features in a more desired way.

Spatio-temporal Flow Analysis
Tino Weinkauf

Abstract Understanding the processes in time-dependent flows is of crucial importance in many domains. Different methods exist for this purpose. This talk reviews methods that build on a spatio-temporal concept where the temporal dimension is treated on equal footing with the spatial dimensions. This means, an n-dimensional unsteady flow is analyzed as an (n+1)-dimensional steady flow. This has led to a number of powerful analysis and visualization methods in the last decade such as Feature Flow Fields [25], [23], Swirling Motion Cores [20], Streak Lines as Tangent Curves [21], [22], and more. The talk will cover the range from theoretical foundations to the applications on real data.

Flow Analysis with Robustness
Bei Wang

Abstract This talk will review topological approaches for flow visualization. In particular, we will discuss a recent line of research that spans feature extraction, feature tracking, and feature simplification of vector fields based upon the topological notion of robustness that captures structural stability of the data. Robustness, a concept similar to persistent homology, quantifies the stability of critical points with

- *Jun Tao is with University of Notre Dame. E-mail: jtao1@nd.edu.*
- *Hanqi Guo is with Argonne National Laboratory. Email: hguo@anl.gov.*
- *Bei Wang is with University of Utah. Email: beiwang@sci.utah.edu.*
- *Christoph Garth is with University of Kaiserslautern. Email: garth@cs.uni-kl.de.*
- *Tino Weinkauf is with KTH Stockholm. Email: weinkauf@kth.se.*

respect to the minimum amount of perturbation in the fields required to remove them. We will discuss how this line of work can potentially increase the interpretability of data, specifically, by giving a coherent and multi-scale view of the flow dynamics under both stationary and time-varying settings. We will demonstrate how robustness-based approaches are independent of the topological skeleton and are scalable to large-scale datasets.

Vector Field Techniques for Large-Scale Data
Christoph Garth

Abstract Large-scale vector fields as arising from modern scientific computing and experimental workflows pose substantial and significant challenges to visualization. While there is a rich body of work addressing flow visualization, many methods are unable to scale to modern data set sizes both algorithmically and with respect to the complexity of the obtained results. In his talk, he will discuss the application of flow visualization techniques to large-scale, time-varying vector fields, and report on recent research results in this area. Particular attention will be given to parallel algorithms and in-situ techniques that eschew the requirement to store full-fidelity data to achieve accurate visualization. On the latter topic, the talk will discuss several methods to flexibly analyse vector field data at reduced resolution. To conclude, recent results for large-scale vector field ensembles will be discussed.

Scalable Ensemble and Uncertain Flow Field Visualization
Hanqi Guo

Abstract This talk covers both theoritical foundations and scalability studies in ensemble and uncertain flow visualization. As the growth of computation powers, scientists can generate ensembles of flow simulations, or flows with uncertainties, but it remains a great challenge to visualize and understand such data. First, features in flow visualization, such as FTLE and LCS, must be redefined for ensemble and uncertain flows. We review the traditional and direct visualization techniques, as well as advances in this topic, such as coupled field line tracing and analysis in numerical ensembles, comparative ensemble flow visualization, and the the measurement of flow divergence in uncertain unsteady flows. Second, the analysis of uncertain and ensemble and uncertain flows require scalability. We review the scalable algorithms to advect particles in ensemble and uncertain flows, because they play the central role in flow analysis and consumes majority computation time. New techniques in flow data management and stochastic particle tracing are covered, which can help scientists analyze ensemble and uncertain flows at scale.

TUTORIAL NOTES

The tutorial notes will consist of the description of the tutorial, copies of the slides for each talk, and an extensive bibliography including specific references used in the tutorial as well as a general selection of relevant references.

SPEAKERS

The background of each speaker is listed in alphabetical order.

Christoph Garth
University of Kaiserslautern
garth@cs.uni-kl.de
`http://vis.uni-kl.de/people/garth/`

Christoph Garth is an assistant professor in the Computer Science Dept. at the University of Kaiserslautern, Germany. His main research interests include visualization and analysis of large-scale, multi-modal data as well as time-varying vector field visualization, with an emphasis on topology-based methods and in situ techniques.

RELEVANT PUBLICATIONS

[1] A. Agranovsky, H. Obermaier, C. Garth, and K. I. Joy, "A multi-resolution interpolation scheme for pathline based lagrangian flow representations," in *Proceedings of IS&T/SPIE Conference on Visualization and Data Analysis*, 2015.

[2] T. Biedert and C. Garth, "Contour tree depth images for large data visualization," in *Proceedings of the 15th Eurographics Symposium on Parallel Graphics and Visualization*, 2015, pp. 77–86.

[3] A. Agranovsky, D. Camp, C. Garth, E. Bethel, K. I. Joy, and H. Childs, "Improved post hoc flow analysis via lagrangian representations," in *IEEE Symposium on Large Data Analysis and Visualization*, 2014, pp. 67–75.

[4] M. Hummel, H. Obermaier, C. Garth, and K. I. Joy, "Comparative visual analysis of lagrangian transport in CFD ensembles," *IEEE Transactions on Visualization and Computer Graphics*, vol. 19, no. 12, pp. 2743–2752, 2013.

[5] S. Barakat, C. Garth, and X. Tricoche, "Interactive computation and rendering of finite-time lyapunov exponent fields," *IEEE Transactions on Visualization and Computer Graphics*, vol. 18, no. 8, pp. 1368–1380, 2012.

Hanqi Guo
Argonne National Laboratory
hguo@anl.gov
`http://www.mcs.anl.gov/~hguo/`

Hanqi Guo is a Postdoctral Appointee in the Mathematics and Computer Science Division, Argonne National Laboratory. He received his PhD degree in computer science from Peking University in 2014, and the BS degree in mathematics and applied mathematics from Beijing University of Posts and Telecommunications in 2009. His research interests are mainly on uncertainty visualization, flow visualization, and large-scale scientific data visualization.

RELEVANT PUBLICATIONS

[6] H. Guo, W. He, T. Peterka, H.-W. Shen, S. M. Collis, and J. J. Helmus, "Finite-time lyapunov exponents and lagrangian coherent structures in uncertain unsteady flows," *IEEE Transactions on Visualization and Computer Graphics*, 2016, to appear.

[7] R. Liu, H. Guo, J. Zhang, and X. Yuan, "Comparative visualization of vector field ensembles based on longest common subsequence," to appear, 2016.

[8] H. Guo, J. Zhang, R. Liu, L. Liu, X. Yuan, J. Huang, X. Meng, and J. Pan, "Advection-based sparse data management for visualizing unsteady flow," *IEEE Transactions on Visualization and Computer Graphics*, vol. 20, no. 12, pp. 2555–2564, 2014.

[9] H. Guo, X. Yuan, J. Huang, and X. Zhu, "Coupled ensemble flow line advection and analysis," *IEEE Transactions on Visualization and Computer Graphics*, vol. 19, no. 12, pp. 2733–2742, 2013.

Jun Tao
University of Notre Dame
jtao1@nd.edu
`http://www.nd.edu/~jtao1/`

Jun Tao is currently a postdoctoral researcher at University of Notre Dame. He received a PhD degree in computer science from Michigan Technological University in 2015. His major research interest is scientific visualization, especially on applying information theory, optimization techniques, and topological analysis to flow visualization and multivariate data exploration. He is also interested in graph-based visualization, image collection visualization, and software visualization. He received the Deans Award for Outstanding Scholarship and the Finishing Fellowship at Michigan Technological University in 2015, and a Best Paper Award at IS&T/SPIE VDA 2013.

Relevant Publications

[10] J. Tao, C. Wang, and C.-K. Shene, “FlowString: Partial streamline matching using shape invariant similarity measure for exploratory flow visualization,” in *Proceedings of IEEE Pacific Visualization Symposium*, 2014, pp. 9–16.

[11] J. Tao, C. Wang, C.-K. Shene, and S. H. Kim, “A deformation framework for focus+context flow visualization,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 20, no. 1, pp. 42–55, 2014.

[12] J. Tao, J. Ma, C. Wang, and C.-K. Shene, “A unified approach to streamline selection and viewpoint selection for 3D flow visualization,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 19, no. 3, pp. 393–406, 2013.

[13] J. Tao, C. Wang, C.-K. Shene, and R. A. Shaw, “A vocabulary approach to partial streamline matching and exploratory flow visualization,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 22, no. 5, pp. 1503–1516, 2016.

[14] M. Wang, J. Tao, J. Ma, Y. Shen, and C. Wang, “FlowVisual: A visualization app for teaching and understanding 3d flow field concepts,” in *Proceedings of IS&T Conference on Visualization and Data Analysis*, San Francisco, CA, 2016.

Bei Wang
University of Utah
beiwang@sci.utah.edu
`http://www.sci.utah.edu/~beiwang/`

Bei Wang is an assistant professor at the School of Computing and the Scientific Computing and Imaging Institute, University of Utah. Her main research interests lie in the theoretical, algorithmic, and application aspects of data analysis and data visualization, with a focus on topological techniques. She is also interested in computational biology and bioinformatics, machine learning and data mining. She is a member of ACM and IEEE.

Relevant Publications

[15] P. Skraba, P. Rosen, B. Wang, G. Chen, H. Bhatia, and V. Pascucci, “Critical point cancellation in 3d vector fields: Robustness and discussion,” *IEEE Transactions on Visualization and Computer Graphics*, 2016, PacificVis Best Paper, to appear.

[16] P. Skraba, B. Wang, G. Chen, and P. Rosen, “Robustness-based simplification of 2d steady and unsteady vector fields,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 21, no. 8, pp. 930–944, 2015.

[17] P. Skraba and B. Wang, “Interpreting feature tracking through the lens of robustness,” in *Topological Methods in Data Analysis and Visualization III*, 2014, pp. 19–37.

[18] P. Skraba, B. Wang, G. Chen, and P. Rosen, “2D vector field simplification based on robustness,” in *Proceedings of IEEE Pacific Visualization Symposium*, Best Paper, 2014, pp. 49–56.

[19] B. Wang, P. Rosen, P. Skraba, H. Bhatia, and V. Pascucci, “Visualizing robustness of critical points for 2d time-varying vector fields,” in *Computer Graphics Forum*, vol. 32, 2013, pp. 221–230.

Tino Weinkauf
KTH Stockholm
weinkauf@kth.se
`http://www.csc.kth.se/~weinkauf/`

Tino Weinkauf received his diploma in computer science from the University of Rostock in 2000. From 2001, he worked on feature-based flow visualization and topological data analysis at Zuse Institute Berlin. He received his Ph.D. in computer science from the University of Magdeburg in 2008. In 2009 and 2010, he worked as a postdoc and adjunct assistant professor at the Courant Institute of Mathematical Sciences at New York University. He started his own group in 2011 on Feature-Based Data Analysis in the Max Planck Center for Visual Computing and Communication, Saarbrcken. Since 2015, he holds the Chair of Visualization at KTH Stockholm. His current research interests focus on flow analysis, discrete topological methods, and information visualization.

Relevant Publications

[20] T. Weinkauf, J. Sahner, H. Theisel, and H.-C. Hege, “Cores of swirling particle motion in unsteady flows,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 13, no. 6, pp. 1759–1766, Nov. 2007.

[21] T. Weinkauf, H.-C. Hege, and H. Theisel, “Advected tangent curves: A general scheme for characteristic curves of flow fields,” *Computer Graphics Forum*, vol. 31, no. 2, pp. 825–834, May 2012.

[22] T. Weinkauf and H. Theisel, “Streak lines as tangent curves of a derived vector field,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 16, no. 6, pp. 1225–1234, Nov. 2010, Received the Vis 2010 Best Paper Award.

[23] T. Weinkauf, H. Theisel, A. Van Gelder, and A. Pang, “Stable Feature Flow Fields,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 17, no. 6, pp. 770–780, Jun. 2011.

[24] T. Stter, T. Weinkauf, H.-P. Seidel, and H. Theisel, “Implicit integral surfaces,” in *Proceedings of International Workshop on Vision, Modeling and Visualization*, Magdeburg, Germany, Nov. 2012, pp. 127–134.

Other References

[25] H. Theisel and H.-P. Seidel, “Feature flow fields,” in *Data Visualization*, 2003, pp. 141–148.