Report from Dagstuhl Seminar 16142

Multidisciplinary Approaches to Multivalued Data: Modeling, Visualization, Analysis

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 16142, "Multidisciplinary Approaches to Multivalued Data: Modelling, Visualization, Analysis", which was attended by 27 international researchers, both junior and senior. Modelling multivalued data using tensors and higher-order descriptors has become common practice in neuroscience, engineering, and medicine. Novel tools for image analysis, visualization, as well as statistical hypothesis testing and machine learning are required to extract value from such data, and can only be developed within multidisciplinary collaborations. This report gathers abstracts of the talks held by participants on recent advances and open questions related to these challenges, as well as an account of topics raised within two of the breakout sessions.

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Edited in cooperation with Andrada Ianuş

1 Executive Summary

Ingrid Hotz
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Topics and Motivation

This seminar is the sixth in a series of Dagstuhl Seminars devoted to the use of tensor fields and other higher order descriptors, including higher-order tensors or Spherical Harmonics, to model intricate multivalued data that arises in modern medical imaging modalities, as well as in simulations in engineering and industry. Even though the literature on image analysis, visualization, as well as statistical hypothesis testing and machine learning is quite rich for scalar or vector-valued data, relatively little work has been performed on these disciplines for tensors and higher-order descriptors.

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Applications wherein such descriptors can be employed to process multivalued data range from neuroimaging to image analysis and engineering. Diffusion Weighted Magnetic Resonance Imaging (DW-MRI), an MRI modality which makes it possible to visualize and quantify structural information about white matter pathways in the brain *in vivo,* is one of the driving technologies, but tensors have also shown their usefulness as feature descriptors for segmentation and grouping in image analysis, including structure tensors and tensor voting. Applications in solid mechanics, civil engineering, computational fluid dynamics and geology require the processing of tensor fields as part of domain-specific modeling, simulation, and analysis (e.g. stress-strain relationships, inertia tensors, permittivity tensor).

The Dagstuhl seminar provides a unique platform by facilitating scientific exchange between key researchers in seemingly diverse applications. Despite these disciplines' commonalities in terms of the tools employed, it would be very unlikely that these scientists would attend the same conference as the theme of most conferences is defined by a specific application. By bringing together specialists in visualization, image processing, statistics, and numerical mathematics, the Dagstuhl seminar provides new impulses for methodological work in those areas.

Organization of the Seminar

To ensure a steady inflow of new ideas and challenges, we put an emphasis on inviting researchers who previously did not have the opportunity to attend one of the meetings in this series. This was true for almost half the attendees in the final list of participants.

The seminar itself started with a round of introductions, in which all participants presented their area of work within 100 seconds with help of a single slide. This helped to create a basis for discussion early on during the week, and was particularly useful since participants came from different scientific communities, backgrounds, and countries.

A substantial part of the week was devoted to presentations by 26 participants, who spent 20 minutes each on presenting recent advances, ongoing work, or open challenges, followed by ten minutes of discussion in the plenary, as well as in-depth discussions in the breaks and over lunch. Abstracts of the presentations are collected in this report. For the traditional social event on Wednesday, we went on a hike, which was joined by almost all participants, and offered additional welcome opportunities for interaction.

Three breakout sessions were organized in the afternoons, and another one in the evening, so that none of them took place in parallel, and everyone had the opportunity to visit all groups relevant to him or her. The topics of the four groups were formed by clustering topics brought up in the round of introductions, and were denoted as:

- Visual encodings and the interface between theory and applications
- Models and geometry
- Topological methods
- Multi-field and tensor group analysis

Depending on the interests of the participants, the breakout groups differed in nature, ranging from the collection of open questions and discussions on future directions of the field to spontaneous tutorial-style presentations. Notes taken during these sessions, and the main results of two of them are summarized in this report.

Outcomes

The participants all agreed that the meeting was successful and stimulating, and we plan to publish another Springer book documenting the results of the meeting. Participants have pre-registered thirteen chapters already during the seminar, and we are in the process of collecting additional contributions both from participants and from researchers working on closely related topics who could not attend the meeting. We expect that the book will be ready for publication in 2017.

It was voted that the group will apply for another meeting in this series. In addition to the current organizers Thomas Schultz (University of Bonn, Germany) and Evren Özarslan (Linköpings Universitet, Sweden), Andrea Fuster (TU Eindhoven, The Netherlands) and Eugene Zhang (Oregon State University, USA) agreed to help apply for the next event.

Acknowledgments

The organizers thank all the attendees for their contributions and extend special thanks to the team of Schloss Dagstuhl for helping to make this seminar a success. As always, we enjoyed the warm atmosphere, which supports formal presentations as well as informal exchange of ideas.

2 Table of Contents

Overview of Talks

Panel discussions

3 Overview of Talks

3.1 Composite Networks: Joint Structural-Functional Modeling of Brain

Burak Acar (Bogaziçi University – Istanbul, TR)

Brain has long been known to be a collection of inter-connected units with a complex signaling mechanism. Our understanding of the brain has evolved from models composed of single-units responsible for tasks and their inter-connectivity towards multiple inter-connected units jointly responsible for tasks. This shift boosted research efforts on brain network analysis that has been grouped as functional and structural networks.

Functional networks (fNETs) are based on the assumption that coherence between spatially distant nodes of an fNET can be observed as the correlation between observed signals, which range from EEG, MEG to fMRI. Challenged by spatial resolution (EEG, MEG), temporal resolution (fMRI) and noise, the fNET models were provided with the substrate they needed, the structural networks (sNET), by the diffusion MRI (dMRI) which is the unique modality for in-vivo imaging of brain structure, albeit its spatial resolution limitations.

Integrating these complementary models is a major challenge towards a deeper understanding of how the brain works. While overcoming the aforementioned temporal and spatial resolution of fMRI and dMRI would be a major milestone on the road, composite network modeling requires more. The major question is whether there is a causal relationship between structure and function. This question manifests in various ways: Is there a priority / hierarchy relationship between structure and function? Who comes first? Do they change roles? Can one serve as a constraint / bias for the other? etc.

A practical approach to the big problem could be to pursue a clinical perspective. In other words, it seems promising to ask how one can answer the clinical questions best by considering the structure and function simultaneously. Our on-going multi-center BRAINetc project pursues this path for the Alzheimer's Disease (AD).

3.2 Interpolation of orientation distribution functions in diffusion weighted imaging

Maryam Afzali-Deligani (Sharif University of Technology – Tehran, IR)

Diffusion weighted imaging (DWI) is a non-invasive method for investigating the brain white matter structure and can be used to evaluate fiber bundles. However, due to practical constraints, DWI data acquired in clinics are low resolution. We propose a method for interpolation of orientation distribution functions (ODFs). To this end, fuzzy clustering is applied to segment ODFs based on the principal diffusion directions (PDDs). Next, a cluster is modeled by a tensor so that an ODF is represented by a mixture of tensors. For interpolation, each tensor is rotated separately. The proposed method is appropriate for increasing resolution in the ODF field and can be applied to clinical data to improve evaluation of white matter fibers in the brain.

3.3 Towards the Processing of Rotation Fields

Bernhard Burgeth (Universität des Saarlandes, DE), Andreas Kleefeld (Universität des Saarlandes, DE)

A rotation field can be considered as a mapping from an image domain into the set of orthonormal $n \times n$-matrices, $n = 2, 3, \ldots$ with determinant $+1$. Rotation fields might originate from fields of symmetric matrices via eigendecomposition and as such potentially play a role, for example, in medical imaging and material science. Although orthonormal matrices have many algebraic properties it is not clear how to extend image processing methods to this type of data. Even standard interpolation of orthonormal matrices is not straight forward. In this talk we present approaches to create building blocks (averaging, supremum, infimum etc.) for elementary image processing of rotation fields. After presenting some preliminary results we will discuss prerequisites, shortcomings, and potential of the proposed concepts.

3.4 Geometrical Modeling in Diffusion MRI: From Riemann to Finsler

Tom Dela Haije (TU Eindhoven, NL), Luc Florack (TU Eindhoven, NL), and Andrea Fuster (TU Eindhoven, NL)

In geometrical modeling of diffusion MRI, spin dynamics in space are assumed to correspond to a simple stochastic (Brownian) process on a manifold. In this work we introduce the basic concepts of two geometrical models used in diffusion MRI, in which the tissue is modeled as either a Riemannian or a Finslerian manifold. The Riemannian framework for diffusion MRI was originally proposed in 2002, and since then considerable effort has been made to extend it to the more complex Finslerian case. We recently introduced a canonical definition for the Finslerian geometrical structure in terms of the diffusion MRI signal, which solves one of the major hurdles discussed at the last Dagstuhl meeting.

3.5 Bayesian heteroscedastic Rice regression for diffusion tensor imaging

Anders Eklund (Linköping University, SE)

Joint work of Anders Eklund, Bertil Wegmann, Mattias Villani

Diffusion weighted imaging (DWI) has during the last years been improved using better MR scanners and more advanced gradient sequences. In this presentation, the focus will instead be on improving the statistical analysis. For example, to estimate a diffusion tensor in each voxel, a standard approach is to take the logarithm of the measurements and then calculate the best parameters using least squares or weighted least squares. Additionally, the standard approaches only return a point estimate of the tensor, and ignore the uncertainty of the estimates (which may be important for a group analysis). A more proper way to estimate the tensor parameters is to use a generalized linear model with a logarithmic link function. Using a Bayesian framework, a (posterior) distribution of the tensor parameters will be achieved, instead of a point estimate. Specifically, the use of a generalized linear model with support for heteroscedastic (non-stationary variance) Rician noise will be discussed in this presentation.

3.6 New possibilities with shortest-path tractography

Aasa Feragen (University of Copenhagen, DK)

Joint work of Niklas Kasenburg, Michael Schober, Matthew Liptrot, Nina Reislev, Silas Ørting, Mads Nielsen, Ellen Garde, Philipp Hennig, Søren Hauberg, Aasa Feragen
Main reference N. Kasenburg, M. Liptrot, N. Linde Reislev, S. N. Ørting, M. Nielsen, E. Garde, A. Feragen, "Training shortest-path tractography: Automatic learning of spatial priors", NeuroImage, Vol. 130, pp. 63–76, 2016.
URL http://dx.doi.org/10.1016/j.neuroimage.2016.01.031
Main reference S. Hauberg, M. Schober, M. Liptrot, P. Hennig, A. Feragen, "A Random Riemannian Metric for Probabilistic Shortest-Path Tractography", in Proc. of the 18th Int'l Conf. on Medical Image Computing and Computer-Assisted Intervention (MICCAI'15), LNCS, Vol. 9349, pp. 597–604, Springer, 2015.
URL http://dx.doi.org/10.1007/978-3-319-24553-9_73

Tractography is a family of algorithms that aim to estimate the trajectories of brain fibers from noisy diffusion weighted MRI data. The most typical approach for estimating such trajectories is *fiber tracking*, where the algorithm starts at a pre-selected seed point and keeps walking in an estimated "most likely" direction until a stopping criterion is reached. Tracking methods suffer from "path length dependency" which results in a) propagation of uncertainty with distance to the seed point, and b) decrease in the probability of ever reaching a target point with its distance to the seed point, regardless of whether there is a physical connection or not.

An alternative approach is *shortest-path tractography* (SPT), which reformulates tractography as a shortest path problem either on a graph or in a Riemannian manifold. I will discuss two new tools made possible by shortest-path tractography:

- Learning spatial priors for graph-based SPT, allowing learned or existing prior knowledge to improve tractography output.
- Representing tractography output as a Gaussian Process probability distriution over curves in a Riemannian manifold, allowing uncertainty estimates that do not propagate with seed point distance.

3.7 Cartan Scalars in Finsler-DTI for Higher Order Local Brain Tissue Characterization

Luc Florack (TU Eindhoven, NL), Tom Dela Haije (TU Eindhoven, NL), and Andrea Fuster (TU Eindhoven, NL)

Joint work of Luc Florack, Andrea Fuster, Tom Dela Haije
Main reference L. M. J. Florack, T. C. J. Dela Haije,A. Fuster, "Direction-controlled DTI interpolation", in I. Hotz, T. Schultz (eds.), "Visualization and Processing of Tensors and Higher Order Descriptors for Multi-Valued Data", Mathematics and Visualization, pp. 149–162, Springer, 2015.
URL http://dx.doi.org/10.1007/978-3-319-15090-1
Main reference L. M. J. Florack, A. Fuster, "Riemann-Finsler geometry for diffusion weighted magnetic resonance imaging", in C. F. Westin, A. Vilanova, B. Burgeth (eds.), "Visualization and Processing of Tensors and Higher Order Descriptors for Multi-Valued Data", Mathematics and Visualization, pp. 189–208, Springer, 2014.
URL http://dx.doi.org/10.1007/978-3-642-54301-2

In diffusion weighted magnetic resonance imaging (dwMRI) there is a need for "higher order" data representations. Geometric representations are of particular interest. In previous work we advocated the use of Finsler geometry to generalize the Riemannian framework developed in the context of diffusion tensor imaging (DTI). The latter stipulates that diffusivity along a path can be quantified in terms of a data-adapted "length" functional, for which the (inverse) DTI tensor provides the defining Gram matrix for an inner product norm (6 d.o.f.'s per spatial position). The Finsler-DTI extension likewise stipulates a data-adapted length functional in terms of a second order tensor. The corresponding norm is given by a generalized "Finsler-DTI" tensor that lives on a 5-dimensional manifold of space and orientation (formally 6 d.o.f.'s, but effectively reducible to a single d.o.f. per spatial position and orientation). Unlike with DTI, this Finsler norm is not (necessarily) induced by an inner product, and admits an unlimited number of local d.o.f.'s (with each orientation treated as an a priori independent variable). The (third order) Cartan tensor of Finsler geometry captures the residual d.o.f.'s discarded in the classical Riemann-DTI rationale. It is of interest to study scalars induced by this tensor, as they disclose features of local fiber architecture that DTI fails to capture. As such they complement well-known ones from classical DTI, such as fractional isotropy, and are amenable to traditional image analysis techniques for classification, visualization, etc.

3.8 What do the Universe and the brain have in common?

Andrea Fuster (TU Eindhoven, NL)

In this talk I investigate similarities between techniques used in the analysis and visualization of astronomy and brain imaging data.

3.9 Moment Invariants for multi-dimensional Data

Hans Hagen (TU Kaiserslautern, DE) and Roxana Bujack (TU Kaiserslautern, DE)

Moment invariants have long been successfully used for pattern matching in scalar fields. By their means, features can be detected in a data set independent of their exact orientation, position, and scale. Their recent extension to vector fields was the first step towards rotation invariant pattern detection in multi-dimensional data. We research the state of the art on moment invariants for vector valued data and evaluate the potential of the different approaches for the next step of generalizing moment invariants to tensor fields.

3.10 Anisotropic Sampling for Texture Generation and Glyph Distribution

Ingrid Hotz (Linköping University, SE)

Joint work of Andrea Kratz, Ingrid Hotz
Main reference A. Kratz, D. Baum, I. Hotz, “Anisotropic Sampling of Planar and Two-Manifold Domains for Texture Generation and Glyph Distribution”, Transaction on Visualization and Computer Graphics, 19(11):1782–1794, IEEE, 2013.
URL http://dx.doi.org/10.1109/TVCG.2013.83

Anisotropic sample distributions on planar and two-manifold domains are useful for many applications. Our work has been motivated by generating uniform but still aperiodic glyph distributions and texture generation. The requirement for the sampling is being dense, covering the entire surface and being aperiodic to not generating artificial visual patterns. A second requirement for our work is efficiency and robustness. The sample generation should be interactive and work without tedious parameter tuning even for rapidly changing size and orientation of the samples. To reach this goal we employ an anisotropic triangulation that serves as basis for the creation of an initial sample distribution as well as for a gravitational-centered relaxation. Furthermore, define anisotropic Voronoi cells as base element for texture generation. It represents a novel and flexible visualization approach to depict metric tensor fields that can be derived from general tensor fields as well as scalar or vector fields.

3.11 Advanced diffusion MRI for microstructure imaging

Andrada Ianuş (University College London, GB)

Joint work of Andrada Ianuş, Ivana Drobnjak, Gary Hui Zhang, Enrico Kaden, Daniel C. Alexander
Main reference I. Drobnjak, H. Zhang, A. Ianuş, E. Kaden, D. C. Alexander, "PGSE, OGSE, and sensitivity to axon diameter in diffusion MRI: Insight from a simulation study", Magn Reson Med., 75(2):688–700, 2016.
URL http://dx.doi.org/10.1002/mrm.25631
Main reference A. Ianus, I. Drobnjak, D. C. Alexander, "Model-based estimation of microscopic anisotropy using diffusion MRI: a simulation study", NMR in Biomedicine, 29(5):672–685, 2016.
URL http://dx.doi.org/10.1002/nbm.3496

Diffusion weighted MRI (DW-MRI) probes the displacement of water molecules inside the tissue, which is influenced by the presence of cellular membranes. Microstructure imaging techniques use mathematical models which describe the effect of various tissue properties (e.g. cellular size, shape, volume fraction, etc) on the acquired signal and fits them to the data, in order to infer microscopic features from images that have a much lower resolution (usually at the millimetre scale). Here I present some of the current and future directions of microstructure imaging techniques developed in our group, with applications to both brain and cancer imaging.

The first part is focused on applications of microstructure imaging in the brain. Measuring axon diameter provides potential biomarkers for staging and monitoring the progression of white matter diseases such as multiple sclerosis, as well as for understanding the ageing process. The current techniques for mapping axon diameter, such as AxCaliber or Active Ax, use a collection of standard single diffusion encoding (SDE) sequences, which do not provide the optimal sensitivity to axon diameter. We have compared in simulation the sensitivity of SDE and oscillating diffusion encoding (ODE) sequences to axon diameter, showing that in practical situations of dispersed axons, as well as multiple gradient orientations, ODE sequences are beneficial for estimating axon diameter. We also discuss the resolution limit of this technique, i.e. the smallest diameter that can be distinguished.

The second part is focused on diffusion acquisition and modelling techniques with potential applications for cancer imaging. Cellular anisotropy is an important microstructural feature, which has the potential to distinguish between different types of tumours as well as different tumour grades. A recently developed technique for cancer imaging, namely VERDICT MRI, which uses a collection of SDE sequences and models multi-compartment diffusion, does not account for pore eccentricity. A widely used sequence in the literature for estimating microscopic anisotropy is double diffusion encoding, which vary the gradient orientation within one measurements, however, most of studies do not recover intrinsic estimates of pore size and eccentricity. Here I present a model-based approach that allows the estimation of pore size and eccentricity in complex substrates which consist of elongated pores with a distribution of sizes, as well as a comparison between the ability of SDE and DDE sequences to recover the ground truth microstructural parameters depending on the complexity of the substrates.

3.12 Tract Orientation and Angular Dispersion Deviation Indicator (TOADDI): A framework for single-subject analysis in diffusion tensor imaging

Cheng Guan Koay (Walter Reed Medical Center – Bethesda, US)

The purpose of the proposed framework is to carry out single-subject analysis of diffusion tensor imaging (DTI) data. This framework is termed Tract Orientation and Angular Dispersion Deviation Indicator (TOADDI). It is capable of testing whether an individual tract as represented by the major eigenvector of the diffusion tensor and its corresponding angular dispersion are significantly different from a group of tracts on a voxel-by-voxel basis. This work develops two complementary statistical tests (orientation and shape tests) based on the elliptical cone of uncertainty, which is a model of uncertainty or dispersion of the major eigenvector of the diffusion tensor.

3.13 Magnetic Susceptibility Tensor: Imaging and Modeling

Chunlei Liu (University of California – Berkeley, US)

Magnetic susceptibility is a quantitative measure of the extent to which a material is magnetized by an applied magnetic field. The magnetic susceptibility of a material, noted by χ, is equal to the ratio of the magnetization M within the material to the applied magnetic field strength H, i.e. $\chi = \mathrm{M}/\mathrm{H}$. Susceptibility anisotropy describes that magnetic susceptibility is a tensor quantity rather than a scalar quantity. Susceptibility tensor imaging (STI) was proposed to measure and quantify susceptibility as a rank-2 tensor. This technique relies on the measurement of frequency offsets at different orientations with respect to the main magnetic field. The orientation dependence of susceptibility is characterized by a tensor. In the brain's frame of reference, the relationship between frequency shift and susceptibility tensor is given by:

$$f(\mathbf{k}) = \gamma B_0 \left(\frac{1}{3}\hat{\mathbf{H}}^T \chi(\mathbf{k})\hat{\mathbf{H}} - \hat{\mathbf{H}} \cdot \mathbf{k}\frac{\mathbf{k}^T \chi(\mathbf{k})\hat{\mathbf{H}}}{k^2} \right) \tag{1}$$

Here, χ is a second-order (or rank-2) susceptibility tensor; $\hat{\mathbf{H}}$ is the unit vector (unitless) of the applied magnetic field. Assuming that the susceptibility tensor is symmetric, then there are six independent variables to be determined for each tensor. In principle, a minimum of six independent measurements are necessary. A set of independent measurements can be obtained by rotating the imaging object, e.g. tilting the head, with respect to the main magnetic field. Given a set of such measurements, a susceptibility tensor can be estimated by inverting the system of linear equations formed by Eq. 1. Fewer than six orientations are also feasible by incorporating fiber orientation estimated by diffusion tensor imaging (DTI) and assuming cylindrical symmetry of the susceptibility tensor. Susceptibility tensor can be decomposed into three eigenvalues (principal susceptibilities) and associated eigenvectors. Similar to DTI fiber tractography, fiber tracts can be reconstructed based on STI.

3.14 Visual Integration of Spatial-Nonspatial Data in Engineering

Georgeta Elisabeta Marai (University of Illinois – Chicago, US)

Joint work of Fillipo Pellolio, Chihua Ma, Timothy Luciani, Georgeta Elisabeta Marai

Multifield engineering data features sometimes both spatial and nonspatial characteristics. In the visualization field, “spatial data” denotes datasets whose input attributes specify the position of each item – for example airflow around an airplane wing. In contrast, “nonspatial data” denotes completely abstract datasets in which no attributes have intrinsic spatial position semantics—for example sets or tables. In this context, are tensors spatial or nonspatial quantities? Does the distinction matter? What can we learn from the existing visual integration designs which exist for engineering data?

3.15 Towards the estimation of biomechanical tensors through efficient image processing methods

Rodrigo Moreno (KTH Royal Institute of Technology – Stockholm, SE)

Joint work of Örjan Smedby, Dieter Pahr, Rodrigo Moreno
Main reference R. Moreno, Ö. Smedby, D. H. Pahr, “Prediction of apparent trabecular bone stiffness through fourth-order fabric tensors”, Biomechanics and Modeling in Mechanobiology, 15(4):831–844, Springer, 2015.
URL http://dx.doi.org/10.1007/s10237-015-0726-5

Tensors are widely used in biomechanics to describe different physical properties of tissue. Although diffusion MRI has been very successful describing anisotropy and orientation of tissue non invasively, its use is mainly restricted to certain anatomical sites, such as the brain and muscle fibers. In other applications, tensors can be obtained either through physical experiments or simulations using anatomical images as an input. Both options are inconvenient in clinics as experiments are usually not possible and simulations are time consuming. Alternatively, a good and efficient approximation of these tensors can be obtained by finding connections between geometry descriptors of the tissue and the tensorial variables of interest. In this talk, I will show the use of this approach in two different contexts. In the first one, the stiffness tensor, which is one of the most important biomechanical parameter of trabecular bone, is estimated using fabric tensors [1]. In the second one, the permeability tensor of the microvasculature of the liver, which is important to understand the micro perfusion process in the liver, is also approximated through fabric tensors. In these two applications, the estimations are obtained in just a few seconds with a relatively high accuracy, compared to the very expensive FEM-based approaches. The preliminary results suggest that geometry plays a big role in these physical entities. Our current efforts aim at finding further connections between more advanced geometrical descriptors and different biomechanical tensors.

3.16 Substitutability of Symmetric Second-Order Tensor Fields: An Application in Urban 3D LiDAR Point Cloud

Jaya Sreevalsan Nair (IIIT – Karnataka, IN) and Beena Kumari

Joint work of Beena Kumari, Jaya Sreevalsan-Nair
Main reference B. Kumari, J. Sreevalsan-Nair, "An interactive visual analytic tool for semantic classification of 3D urban LiDAR point cloud", in Proc. of the 23rd SIGSPATIAL Int'l Conf. on Advances in Geographic Information Systems (GIS'15), Article No. 73, ACM, 2015.
URL http://dx.doi.org/10.1145/2820783.2820863

There has been work on augmented semantic classification of 3D urban LiDAR point cloud, which is a tuple of class labels from two different classifications, namely structural and contextual. The goal of augmented semantic classification is to extract curves (boundaries, ridges, etc.) and identify objects (buildings, vegetation, asphalt and natural ground), which will further enable 3D object extraction. The structural classification, which is an essential step in augmented semantic classification, is computed using a multi-scale approach of using structure tensor, which effectively defines di Zenzo multi-valued geometry. Spectral values of the structure tensor have been used frequently in LiDAR community to derive multiple values of local geometry. While the structure tensor, computed probabilistically using covariance matrix, encodes proximity and continuity, we propose the use of an anisotropic diffusion tensor, derived from voting tensor, to encode information on weights on proximity and the global context of the local neighborhood. Our proposed voting tensor additionally uses eigenvector orientation for determining diffusion velocity. The goal of our work is to improve the outcomes of structural classification and the overall augmented classification, where we use unsupervised methods. We further discuss the extent of substitutability of the tensor field, constructed from covariance matrix, with a diffused normal voting tensor field – in addition to the application of classification where the substitution works, we show an application in local geometry extraction where the substitution does not work.

3.17 Characterizing Diffusion Anisotropy with a Confinement Tensor

Evren Özarslan (Linköping University, SE)

We studied the influence of diffusion on NMR experiments when the diffusing molecules are subjected to a force field. We place special emphasis on parabolic (Hookean) potentials, which we tackled theoretically using path integral methods. We obtained explicit relationships for commonly employed gradient waveforms involving pulsed and oscillating gradients. Semi-analytical multiple correlation function (MCF) method as well as random walk simulations validated our theoretical results.

The three-dimensional formulation of the problem leads to a new characterization of diffusional anisotropy. Unlike for the case of traditional methods that employ a diffusion tensor, anisotropy in our model originates from the stiffness tensor of a virtual spring while bulk diffusivity is retained in the formulation. Our approach thus yields an expansive alternative to diffusion tensor imaging (DTI). Contrary to DTI, our technique accounts for the restricted character of the diffusion process as reflected in its diffusion-time dependence. The formalism is expected to be useful in addressing a variety of problems involving macroscopic (global) and microscopic (local) diffusion anisotropy.

3.18 Characterizing microstructural tissue abnormalities in mild traumatic brain injury with diffusion compartment imaging

Benoit Scherrer (Harvard Medical School – Boston, US)

Main reference B. Scherrer, A. Schwartzman, M. Taquet, M. Sahin, S. P. Prabhu, S. K. Warfield, "Characterizing brain tissue by assessment of the distribution of anisotropic microstructural environments in diffusion-compartment imaging (DIAMOND)", in Magn Reson Med, 2015, to appear.

While diffusion tensor imaging (DTI) has proven sensitive to detecting microstructural changes in mild traumatic injury (mTBI), it lacks specificity and fails at providing a mechanistic insight into tissue changes. mTBI is associated with cytotoxic edema, neuroinflammation and traumatic axonal injury (TAI) of varying severity, each of which have a unique intra-voxel diffusion signature when imaging with multiple b-values. Diffusion compartment imaging (DCI) aims at teasing apart the distinct types of diffusion within voxels whenever they are present, providing improved insight into underlying tissues changes. We present recent developments in DCI and provide preliminary evidence that DCI enables more detailed characterization of tissue changes in mTBI with higher sensitivity and specificity.

3.19 Visualization of Third-Order Tensor Fields

Gerik Scheuermann (Universität Leipzig, DE), Markus Stommel (TU Dortmund, DE) and Valentin Zobel (Universität Leipzig, DE)

In some applications, it is necessary to look into gradients of (symmetric) second order tensor fields. These tensors are of third order. In three-dimensional space, we have 18 independent coefficients at each position, so the visualization of these fields provides a challenge. A particular case are stress gradients in structural mechanics. We present specific situations where the stress gradient is required together with the stress to study material behavior. Since the visualization community lacks methods to show these fields, we look at some preliminary ideas to design appropriate glyphs. We motivate our glyph designs by typical depictions of stress in engineering textbooks.

3.20 Along-the-Tract Feature Extraction as a Manifold Learning Problem

Thomas Schultz (Universität Bonn, DE)

Joint work of Mohammad Khatami, Tobias Schmidt-Wilcke, Pia C. Sundgren, Amin Abbasloo, Bernhard Schölkopf, Thomas Schultz
Main reference M. Khatami, T. Schmidt-Wilcke, P. C. Sundgren, A. Abbasloo, B. Schölkopf, T. Schultz, "BundleMAP: Anatomically Localized Features from dMRI for Detection of Disease", in Proc. of the Int'l Workshop on Machine Learning in Medical Imaging (MLMI), LNCS, Vol. 9352, pp. 52–60, Springer, 2015.
URL http://dx.doi.org/10.1007/978-3-319-24888-2_7

Supervised classification and regression based on diffusion MR data require the definition of suitable feature vectors, which are most frequently derived either from individual voxels, or from tractography-based networks. We demonstrate the benefits of an intermediate approach, which aggregates information along fiber bundles, while still preserving the ability to localize the effects of disease. This leads us to revisit the classical problem of along-the-tract analysis, for which we propose a novel, simple yet reliable and stable approach: We consider the joint parametrization of fiber bundles as a problem of mapping to a latent fiber core manifold, which is solved in a simple and stable manner using ISOMAP. We present BundleMAP, an integrated machine learning framework that uses this idea for classification, regression, statistical analysis and visualization, and we discuss its future integration into a multimodal framework.

3.21 Iteratively Reweighted L1-fitting For Model-Independent Outlier Removal And Regularization In Diffusion MRI

Alexandra Tobisch (DZNE – Bonn, DE & Universität Bonn, DE)

Joint work of Alexandra Tobisch, Tony Stöcker, Samuel Groeschel, Thomas Schultz
Main reference A. Tobisch, T. Stöcker, S. Groeschel, T. Schultz, "Iteratively Reweighted L1-fitting For Model-Independent Outlier Removal And Regularization In Diffusion MRI", in Proc. of the IEEE Int'l Symp. on Biomedical Imaging (ISBI'16), pp. 911–914, IEEE, 2016.
URL http://dx.doi.org/10.1109/ISBI.2016.7493413

Diffusion MRI provides the possibility to investigate the structural connectivity of brain white matter non-invasively and to examine pathological conditions of the central nervous system. However, the technique is negatively affected by subject motion occurring during the image acquisition. Spatially and temporally varying artifacts, e.g. induced by subject motion, potentially degrade the signal quality and adversely influence the estimation of microstructural diffusion measures. Especially in clinical applications or large population studies, when data is collected from diseased patients, children or elderly people, measures need to be taken against the image degradation due to frequently occurring motion artifacts. State-of-the-art procedures for outlier removal detect and reject defective images during model fitting. These methods, however, are tailored only for specific diffusion models and excluding a varying number of diffusion-weighted images might be disadvantageous for the parameter estimation. We present a novel method based on an iteratively reweighted L1-Fitting for model-independent outlier removal with subsequent reconstruction of the full set of DWIs from the sparse set of inliers by modeling the signal in the continuous SHORE basis. Our results on simulation data and clinical in vivo human brain scans demonstrate that this method corrects dMRI data for motion artifacts and reduces the impact of defective DWIs on diffusion measures.

3.22 Tractography-based Edge Detection for Diffusion Weighted MRI Analysis

Xavier Tricoche (Purdue University – West Lafayette, US)

Joint work of Ziang Ding, Yaniv Gur, Xavier Tricoche

We present a technique to automatically characterize the geometry of important anatomical structures in diffusion weighted MRI (DWI) data. Our approach is based on the interpretation of diffusion data as a superimposition of multiple line fields that each form a continuum of space filling curves. Using a dense tractography computation, we quantify the spatial variations of the geometry of these curves and use the resulting measure to characterize salient structures as edges. Anatomically, these structures have a boundary-like nature and yield a clear and precise picture of major fiber bundles. Our framework leverages high angular resolution imaging (HARDI) data to offer a precise geometric description of subtle anatomical configurations associated with the local presence of multiple fiber orientations. We evaluate our technique and study its robustness to noise in the context of a phantom dataset and present results obtained with in vivo human and small animal imaging.

3.23 Multivalued Data Processing Techniques for Diffusion MRI

Gözde Ünal (Istanbul Technical University, TR)

This work presents two novel techniques for processing of MRI data in order to extract structural asymmetries. First technique consists of an effective regularization technique for capturing inherent asymmetry of the underlying intravoxel geometry that exists in bending, crossing or kissing fibers of the brain white matter. This, to our knowledge, is the first study that demonstrates the asymmetry at the voxel level. The second technique uses higher order tensors in modelling of tree-like structures such as vascular trees in human brain. We show how we embed the tensor in a 4D space rather than 3D in order to untangle the bifurcating (or even n-furcating) structures/branches in the data in a higher-dimensional space.

3.24 Visual Group-Analysis for Diffusion Tensor Data

Anna Vilanova Bartroli (TU Delft, NL) and Changgong Zhang (TU Delft, NL)

Joint work of Changgong Zhang, Thomas Schultz, Kai Lawonn, Elmar Eisemann, Anna Vilanova Bartroli,
Main reference C. Zhang, T. Schultz, K. Lawonn, E. Eisemann, A. Vilanova, "Glyph-Based Comparative Visualization for Diffusion Tensor Fields", Trans. Vis. Comput. Graph., 22(1):797–806, IEEE, 2016.
URL http://dx.doi.org/10.1109/TVCG.2015.2467435

For several applications it is necessary to compare diffusion tensor fields, e.g., to study the effects of acquisition parameters, or to investigate the influence of pathology on white matter structures. This comparison is commonly done by extracting scalar information out of the tensor fields and then comparing these scalar fields, which leads to a loss of information. If the local full tensor representation,i.e., glyphs is kept representation simple juxtaposition or superposition exist and is used, but they are not efficient visual encodings to identify difference. We propose the Tender Glyph, a glyph that explicitly encodes differences between orientation, shape and scale. However, this is limited to two tensors. Can we extend this concept to the analysis of groups of tensors? What is the box plot diagram of a group of diffusion tensors?

3.25 Upper bound of transition points in a 3D linear tensor field

Yue Zhang (Oregon State University, US)

Transition points are an integral part of the 3D tensor field topology. They are the degenerate points separating wedges and trisectors along a degenerate curve. Much study has focused on locating degenerate points and less focus has been given to automatically extracting transition points. In this research, we provide an analytic formulation that leads to a theoretical upper bound for the number of transition points for any give 3D linear tensor field.

3.26 Feature-Based Visualization of Stress and Fiber Orientation Tensor Fields

Valentin Zobel (Universität Leipzig, DE), Gerik Scheuermann (Universität Leipzig, DE), and Markus Stommel

Main reference V. Zobel, M. Stommel, G. Scheuermann, "Feature-based tensor field visualization for fiber reinforced polymers", in the Proc. of the 2015 IEEE Scientific Visualization Conference (SciVis'15), pp. 49–56, IEEE, 2015.
URL http://dx.doi.org/10.1109/SciVis.2015.7429491

The failure of components made from fiber reinforced polymers depends not only on the stress, it depends also on the fiber orientation. The stress is given by a stress tensor field, the fiber orientation by a fiber orientation tensor field. Both tensor fields have to be considered for the prediction of failure. In our work, we define features which indicate failure for a given load condition in dependence of the fiber orientation. Moreover, we use glyphs to show the given and the desired fiber orientation. Since the fiber orientation can be influenced by the production process, these visualizations help the engineer to obtain fiber orientations which lead to more stable components.

4 Panel discussions

4.1 Visual Encodings and Theory/Application Interface

Georgeta Elisabeta Marai (University of Illinois – Chicago, US), Maryam Afzali-Deligani (Sharif University of Technology – Tehran, IR), Bernhard Burgeth (Universität des Saarlandes, DE), Ingrid Hotz (Linköping University, SE), Jaya Sreevalsan Nair (IIIT – Karnataka, IN), Anna Vilanova Bartroli (TU Delft, NL), and Yue Zhang (Oregon State University, US)

The panel discussion was motivated by the challenge to design the analysis and visualization tasks in accordance with the application needs. How can analysis results be communicated to the application scientist despite the complexity of the data and the diversity of the applications. The discussion started with two major questions:

1. Which visual encodings should we use for tensor visualization?
2. How application-specific must these encodings be?

The result of a very vivid and controversial discussion was the agreement that the basis for the development of meaningful analysis and visual representations is a proper classification maybe resulting in a kind of 'tensor catalog' in terms of

- applications with their specific needs, questions and problems,
- tensor type from of mathematical as well as a semantic point of view,
- specific data related challenges.

Especially for the work within the field of tensor field visualization the idea of 'one-size fits all' is problematic. It was recognized that there is some useful work dealing with this task however it is still far from being complete. Examples that have been discussed were the classification as part of a state of the art report "Visualization and Analysis of Second-Order Tensors: Moving Beyond the Symmetric Positive-Definite Case" by Kratz et al. or the introduction of diverse parametrizations of the space of tensor fields as in "Asymmetric tensor analysis for flow visualization" by Zhang et al. or "Orthogonal Tensor Invariants and the Analysis of Diffusion Tensor Magnetic Resonance Images" by Ennis et al.

During the break-out session, we started with a collection of keywords which might be relevant for the classification which is stated below. However, due to the limited time, it did not get beyond the current state of the art. However, it demonstrated clearly that there is the the need to approach this task in a more concise way.

Keyword collection:

1. Type and properties: symmetry, definiteness, sparseness, invertibility, co- and contravariance
2. Problem characteristics: scale of data sets, dimension (2d/3d/Nd,time-dependent), grid structure
3. Features of interest: principal directions (eigenvectors), rotational features, topology, discontinuity

4. Visualizations: level of detail, summarization, statistics, clustering
5. The encodings: colors, Glyphs, tensorlines, Topology, Volume Rendering

4.2 Multifield tensor analysis – group tensor analysis

Anna Vilanova Bartroli (TU Delft, NL)

In this break out session, we discussed the analysis of groups of tensors. The following notes have been taken:

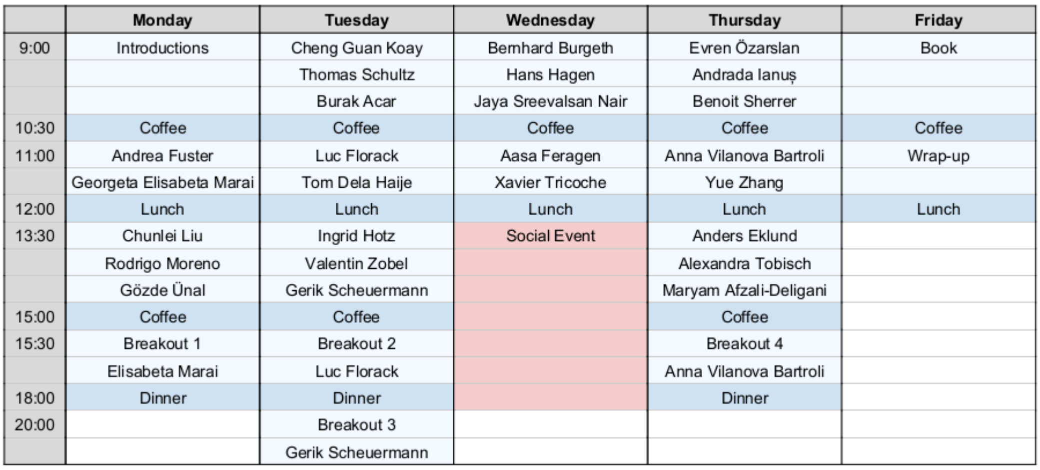
- Analysis of group of tensors field is interesting for several reasons: Comparison between two fields, Uncertainty description, population description, comparison between populations We discussed mathematical/statistical frameworks that exist to analyze this data
- Data tensors might be of interest to be used in this context. They can be used to summarize a whole population. Methods like alternating least squares. How do you preserve the tensor structure in such a context? This was unclear for some of the participants. Relevant literature includes:
  - Tensor Decompositions and Applications, Tamara G. Kolda, and Brett W. Bader, SIAM review
  - Renato Pajarola has also done work in this direction in the visualization community
- There are methods in the literature to calculate means and tensor covariance matrices. We discussed some of these approaches. Usually, they are coupled to different distance metrics for tensors that have been defined in the past. Relevant literature:
  - Spectral decomposition of a 4th-order covariance tensor: Applications to diffusion tensor MRI – Peter J. Basser and Sinisa Pajevic
  - Statistics on the Manifold of Multivariate Normal Distributions: Theory and Application to Diffusion Tensor MRI Processing – Christophe Lenglet and Mikaël Rousson
- Mathematical framework for multi-tensor models: Linear combination of multi-tensor models for registration, atlasing and detection of statistically significant differences along fascicles using null hypothesis testing (using clustered-based statistics)
  - A Mathematical Framework for the Registration and Analysis of Multi-Fascicle Models for Population Studies of the Brain Microstructure, Maxime Taquet, Benoit Scherrer, Olivier Commowick, Jurriaan Peters, Mustafa Sahin, Benoit Macq and Simon K. Warfield, IEEE Transactions on Medical Imaging, 2014 http://perso.uclouvain.be/maxime.taquet/documents/taquet_tmi2013.pdf
  - A Framework for the Analysis of Diffusion Compartment Imaging (DCI), Maxime Taquet, Benoit Scherrer and Simon K. Warfield, in Visualization and Processing of Tensors and Higher Order Descriptors for Multi-Valued Data, Springer 2015. http://perso.uclouvain.be/maxime.taquet/documents/taquet_springer2014.pdf
- Improvements with a new model that better preserves microstructural features (i.e., "more linear" interpolation of microstructural parameters, less swelling)
- Work on Minkowski tensors with applications in physical applications: http://csgb.dk/research-topics/wp1/
- There is not much visualization research in this direction, to our knowledge, the papers that are there in this direction are:

- Glyph-based Comparative Visualization for Diffusion Tensor Fields Changgong Zhang, Thomas Schultz, Kai Lawonn, Elmar Eisemann, and Anna Vilanova In: IEEE Trans. on Visualization and Computer Graphics (2016), 22:1
- Visualizing Tensor Normal Distributions at Multiple Levels of Detail Amin Abbasloo, Vitalis Wiens, Max Hermann, and Thomas Schultz In: IEEE Trans. on Visualization and Computer Graphics (2016), 22:1

5 List of Previous Meetings in this Seminar Series

- The initial Dagstuhl Perspective Workshop (Seminar 04172, April 2004, Organizers: Hans Hagen and Joachim Weickert) was the first international forum where leading experts on visualization and processing of tensor fields had the opportunity to meet, many for the first time. This workshop identified several key issues and triggered fruitful collaborations that have also led to the first book in this area. ISBN 978-3-540-25032-6.
- The follow-up Dagstuhl meeting (Seminar 07022, January 2007, Organizers: David Laidlaw and Joachim Weickert) was equally successful and the progress achieved is comprised in a second book published with Springer. ISBN 978-3-540-88377-7.
- The third Dagstuhl meeting (Seminar 09302, July 2009, Organizers: Bernhard Burgeth and David Laidlaw) paid special attention to engineering applications of tensors in fluid mechanics, material science, and elastography. It became apparent that these disciplines are facing many open problems in tensor field visualization and processing, and that the appropriate answers would greatly enhance the progress in these fields of engineering. The success of this meeting was documented by a third book authored by the participants. ISBN 978-3-642-27342-1.
- The fourth Dagstuhl meeting (Seminar 11501, December 2011, Organizers: Bernhard Burgeth, CF Westin and Anna Vilanova) witnessed a shift towards higher-order descriptors that went beyond tensors. Its numerous successful results are documented in a fourth Springer book. ISBN 978-3-642-54301-2.
- The fifth Dagstuhl meeting (Seminar 14082, February 2014, Organizers: Bernhard Burgeth, Ingrid Hotz, Anna Vilanova and CF Westin) has seen an increasing interest in statistical analysis and in the use of machine learning methods, as well as in the challenges posed by a novel generation of diffusion MR acquisition techniques. Its results were again collected in a Springer book. ISBN 978-3-319-15090-1.

6 Schedule



	Monday	Tuesday	Wednesday	Thursday	Friday
9:00	Introductions	Cheng Guan Koay	Bernhard Burgeth	Evren Özarslan	Book
		Thomas Schultz	Hans Hagen	Andrada Ianuş	
		Burak Acar	Jaya Sreevalsan Nair	Benoit Sherrer	
10:30	Coffee	Coffee	Coffee	Coffee	Coffee
11:00	Andrea Fuster	Luc Florack	Aasa Feragen	Anna Vilanova Bartroli	Wrap-up
	Georgeta Elisabeta Marai	Tom Dela Haije	Xavier Tricoche	Yue Zhang	
12:00	Lunch	Lunch	Lunch	Lunch	Lunch
13:30	Chunlei Liu	Ingrid Hotz	Social Event	Anders Eklund	
	Rodrigo Moreno	Valentin Zobel		Alexandra Tobisch	
	Gözde Ünal	Gerik Scheuermann		Maryam Afzali-Deligani	
15:00	Coffee	Coffee		Coffee	
15:30	Breakout 1	Breakout 2		Breakout 4	
	Elisabeta Marai	Luc Florack		Anna Vilanova Bartroli	
18:00	Dinner	Dinner		Dinner	
20:00		Breakout 3			
		Gerik Scheuermann			

Participants

- Burak Acar
Bogaziçi University –
Istanbul, TR
- Maryam Afzali-Deligani
Sharif University of Technology –
Tehran, IR
- Bernhard Burgeth
Universität des Saarlandes, DE
- Tom Dela Haije
TU Eindhoven, NL
- Anders Eklund
Linköping University, SE
- Aasa Feragen
University of Copenhagen, DK
- Luc Florack
TU Eindhoven, NL
- Andrea Fuster
TU Eindhoven, NL
- Hans Hagen
TU Kaiserslautern, DE
- Ingrid Hotz
Linköping University, SE
- Andrada Ianuş
University College London, GB
- Cheng Guan Koay
Walter Reed Medical Center –
Bethesda, US
- Chunlei Liu
University of California –
Berkeley, US
- Georgeta Elisabeta Marai
University of Illinois –
Chicago, US
- Rodrigo Moreno
KTH Royal Institute of
Technology – Stockholm, SE
- Jaya Sreevalsan Nair
IIIT – Karnataka, IN
- Jos B.T.M. Roerdink
University of Groningen, NL
- Evren Özarslan
Linköping University, SE
- Benoit Sherrer
Harvard Medical School –
Boston, US
- Gerik Scheuermann
Universität Leipzig, DE
- Thomas Schultz
Universität Bonn, DE
- Alexandra Tobisch
DZNE – Bonn, DE &
Universität Bonn, DE
- Xavier Tricoche
Purdue University –
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- Gözde Ünal
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- Anna Vilanova Bartroli
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- Valentin Zobel
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