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Bio-Inspired Sampling and Reconstruction Framework for Scientific Visualization

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14. ABSTRACT
This project investigated sampling theoretic issues that arise in visualization of 3-D (e.g., in simulation or biomedical) datasets. As sampling and reconstruction are key elements in the visualization pipeline, their mathematical modeling and analysis are foundational to reliability of the resulting visualizations. An important achievement of this investigation is establishing the superiority of optimal lattices for reconstruction of scattered data. These lattices are observed in nature as crystallographic structures (e.g., body centered cubic and face centered cubic lattices), as well as biological vision systems (e.g., hexagonal lattice). While the sampling theoretic advantages of optimal lattices have been established, practical tools (e.g., filtering, interpolation, wavelet analysis, signal reconstruction, regularization methods) for exploiting these advantages have been unavailable to practitioners.

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Abstract

This project investigated sampling theoretic issues that arise in visualization of 3-D (e.g., in simulation or biomedical) datasets. As sampling and reconstruction are key elements in the visualization pipeline, their mathematical modeling and analysis are foundational to reliability of the resulting visualizations. An important achievement of this investigation is establishing the superiority of optimal lattices for reconstruction of scattered data. These lattices are observed in nature as crystallographic structures (e.g., body centered cubic and face centered cubic lattices), as well as biological vision systems (e.g., hexagonal lattice). While the sampling theoretic advantages of optimal lattices have been established, practical tools (e.g., filtering, interpolation, wavelet analysis, signal reconstruction, regularization methods) for exploiting these advantages have been unavailable to practitioners.

This project provides practical algorithms that enable the utilization of these theoretical advantages in context of noisy measurements. In particular, a part of this project demonstrates the superiority of optimal lattices, over the commonly-used Cartesian lattices, for reconstruction of scattered volumetric (3-D) datasets. To that aim, this project provided practical reconstruction algorithms that allow for regularized least-squares solutions generated by spline spaces that are geometrically tailored for these optimal lattices. Uncertainties in the data also impact isosurface (i.e., level-set) extraction methods in visualization. A part of this project investigates the topological and geometric uncertainties that arises in the marching cubes algorithms. This project provides probabilistic models for deciding cell topology and inverse linear interpolation for isosurfacce extraction from uncertain data.

Wenxing Ye; Entezari, A., "Design of bivariate sinc wavelets," in Image Processing (ICIP), 2012 19th IEEE International Conference on , vol., no., pp.2477-2480, Sept. 30 2012-Oct. 3 2012

This paper introduces a new way of constructing 2-D wavelets which generalizes the univariate sinc wavelets to images sampled on arbitrary lattices. For lattices other than Cartesian, such wavelets are no longer tensor products of the univariate version. The proposed construction method is based on the zonotope decomposition of the Brillouin zone of the lattice and can be generalized to all 2-D or 3-D lattices. While our construction allows for the derivation of sinc wavelets for any 2-D lattice, we particularly study the case for the hexagonal lattice. We present experiments that contrast Cartesian tensor-product wavelet decomposition against the non-separable hexagonal wavelet decomposition and demonstrate the increased isotropy in the latter case.

Xie Xu; Alvarado, A.S.; Entezari, A., "Reconstruction of Irregularly-Sampled Volumetric Data in Efficient Box Spline Spaces" , IEEE Transactions on Medical Imaging (TMI), vol.31, no.7, pp.1472-1480, July 2012

We present a variational framework for the reconstruction of irregularly-sampled volumetric data in, non-tensor-product, spline spaces. Motivated by the sampling-theoretic advantages of body centered cubic (BCC) lattice, this paper examines the BCC lattice and its associated box spline spaces in a variational setting. We introduce a regularization scheme for box splines that allows us to utilize the BCC lattice in a variational reconstruction framework. We demonstrate that by choosing the BCC lattice over the commonly-used Cartesian lattice, as the shift-invariant representation, one can increase the quality of signal reconstruction. Moreover, the computational cost of the reconstruction process is reduced in the BCC framework due to the smaller bandwidth of the system matrix in the box spline space compared to the corresponding tensor-product B-spline space. The improvements in accuracy are quantified numerically and visualized in our experiments with synthetic as well as real datasets.

Sun, J.; Xie, Y; Ye, W.; Ho, J., Entezari, A.; Blackband, S.; Vemuri, B.;, Dictionary Learning on the Manifold of Square Root Densities and Applications to Reconstruction of Diffusion Propagator Fields, Information Processing in Medical Imaging (IPMI), vol. 7917, pp.619-631, 2013.

In this paper, we present a novel dictionary learning framework for data lying on the manifold of square root densities and apply it to the reconstruction of diffusion propagator (DP) fields given a multi-shell diffusion MRI data set. This paper leverages optimal sampling lattices to maximize the accuracy of reconstruction from irregularly sampled q-space data. Unlike most of the existing dictionary learning algorithms which rely on the assumption that the data points are vectors in some

Euclidean space, our dictionary learning algorithm is designed to incorporate the intrinsic geometric structure of manifolds and performs better than traditional dictionary learning approaches when applied to data lying on the manifold of square root densities. Non-negativity as well as smoothness across the whole field of the reconstructed DPs is guaranteed in our approach. We demonstrate the advantage of our approach by comparing it with an existing dictionary based reconstruction method on synthetic and real multi-shell MRI data.

Xu, X.; Ye, W.; Entezari, A.;, Bandlimited Reconstruction of Multidimensional Images from Irregular Samples, IEEE Transactions on Image Processing (TIP), vol. 22, no.10, pp.3950-3960, October, 2013.

We examine different sampling lattices and their respective bandlimited spaces for reconstruction of irregularly sampled multidimensional images. Considering an irregularly sampled dataset, we demonstrate that the non-tensor-product bandlimited approximations corresponding to the body-centered cubic and face-centered cubic lattices provide a more accurate reconstruction than the tensor-product bandlimited approximation associated with the commonly-used Cartesian lattice. Our practical algorithm uses multidimensional sinc functions that are tailored to these lattices and a regularization scheme that provides a variational framework for efficient implementation. Using a number of synthetic and real data sets we record improvements in the accuracy of reconstruction in a practical setting.

Athawale, T.; Entezari, A.;, Uncertainty Quantification in Linear Interpolation for Isosurface Extraction, IEEE Transactions on Visualization and Computer Graphics (TVCG), Special Issue on IEEE VIS, vol.19, no.12, pp.2723-2732, December, 2013.

We present a study of linear interpolation when applied to uncertain data. Linear interpolation is a key step for isosurface extraction algorithms, and the uncertainties in the data lead to non-linear variations in the geometry of the extracted isosurface. We present an approach for deriving the probability density function of a random variable modeling the positional uncertainty in the isosurface extraction. When the uncertainty is quantified by a uniform distribution, our approach provides a closed-form characterization of the mentioned random variable. This allows us to derive, in closed form, the expected value as well as the variance of the level-crossing position. While the former quantity is used for constructing a stable isosurface for uncertain data, the latter is used for visualizing the positional uncertainties in the expected isosurface level crossings on the underlying grid.

Suter, S.; Ma, B.; Entezari, A.; Visual Analysis of 3D Data by Isovalue Clustering, Advances in Visual Computing (Proc. of ISVC), Springer Lecture Notes in Computer Science, pp. 313-322, 2014.

Visualization of volumetric data is ubiquitous in data analysis and has been widely used for exploration in scientific simulations and biomedical imaging. While direct and indirect visualization algorithms are employed extensively in applications, the visual exploration of features in the volumetric data is still a laborious task. We present an algorithm to extract exemplar isosurfaces (i.e., level-sets) from a 3D scalar field data set and provide the user with a representative visualization of the data. The presented approach provides an interactive tool that aids in visual analysis and exploration tasks. Our experiments on a number of benchmark data sets suggest that, compared to existing methods, the proposed approach provides a more distinct set of isosurfaces that are more representative of the complexity of the data sets.

Sun, J.; Sakhaee, E.; Entezari, A.; Vemuri, B; Leveraging EAP-Sparsity for Compressed Sensing of MS-HARDI in (k,q)-Space, Information Processing in Medical Imaging (IPMI), vol. 9123, pp. 375-386, 2015.

Compressed Sensing (CS) for the acceleration of MR scans has been widely investigated in the past decade. Lately, considerable progress has been made in achieving similar speed ups in acquiring multi-shell high angular resolution diffusion imaging (MS-HARDI) scans. Existing approaches in this context were primarily concerned with sparse reconstruction of the diffusion MR signal S(q) in the q-space. More recently, methods have been developed to apply the compressed sensing framework to the 6-dimensional joint (k,q)-space, thereby exploiting the redundancy in this 6D space. To guarantee accurate reconstruction from partial MS-HARDI data, the key ingredients of compressed sensing that need to be brought together are: (1) the function to be reconstructed needs to have a sparse representation, and (2) the data for reconstruction ought to be acquired in the dual domain (i.e., incoherent sensing) and (3) the reconstruction process involves a (convex) optimization. In this paper, we present a novel approach that uses partial Fourier sensing in the 6D space of (k,q) for the reconstruction of P(x,r). The distinct feature of our approach is a sparsity model that leverages surfacelets in conjunction with total variation for the joint sparse representation of P(x,r). Thus, our method stands to benefit from the practical guarantees for accurate reconstruction from partial (k,q)-space data. Further, we demonstrate significant savings in acquisition time over diffusion spectral imaging (DSI) which is commonly used as the benchmark for comparisons in reported literature. To demonstrate the benefits of this approach, we present several synthetic and real data examples.

Athawale, T.; Sakhaee, E.; Entezari, A.; Isosurface Visualization of Data with Nonparametric Models for Uncertainty, IEEE Transactions on Visualization and Computer Graphics (TVCG), Special Issue on IEEE VIS, to appear, Dec. 2015.

The problem of isosurface extraction in uncertain data is an important research problem and may be approached in two ways. One can extract statistics (e.g., mean) from uncertain data points and visualize the extracted field. Alternatively, data uncertainty, characterized by probability distributions, can be propagated through the isosurface extraction process. We analyze the impact of data uncertainty on topology and geometry extraction algorithms. A novel, edge-crossing probability based approach is proposed to predict underlying isosurface topology for uncertain data. We derive a probabilistic version of the midpoint decider that resolves ambiguities that arise in identifying topological configurations. Moreover, the probability density function characterizing positional uncertainty in isosurfaces is derived analytically for a broad class of nonparametric distributions. This analytic characterization can be used for efficient closed-form computation of the expected value and variation in geometry. Our experiments show the computational advantages of our analytic approach over Monte-Carlo sampling for characterizing positional uncertainty. We also show the advantage of modeling underlying error densities in a nonparametric statistical framework as opposed to a parametric statistical framework through our experiments on ensemble datasets and uncertain scalar fields.

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Abstract

Th s project nvest gated samp ng theoret c ssues that ar se n v sua zat on of 3-D (e.g., n s mu at on or b omed ca) datasets. As samp ng and reconstruct on are key e ements n the v sua zat on p pe ne, the r mathemat ca mode ng and ana ys s are foundat ona to re ab   ty of the resu t ng v sua zat ons. An mportant ach evement of th s nvest gat on s estab sh ng the super or ty of opt ma   att ces for reconstruct on of scattered data. These att ces are observed n nature as crysta ograph c structures (e.g., body centered cub c and face centered cub c att ces), as we   as b o og ca v s on systems (e.g., hexagona   att ce). Wh e the samp ng theoret c advantages of opt ma   att ces have been estab shed, pract ca too s (e.g., f ter ng, nterpo at on, wave et ana ys s, s gna reconstruct on, regu ar zat on methods) for exp o t ng these advantages have been unava ab e to pract t oners.

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