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Special Issue on Tomography and Neuroscience

Preface

1. Introduction

This special issue of Fundamenta Informaticae concerns Tomography and Neuroscience. It follows the 12^{th} edition of the Meeting on Tomography and Applications, which has been held from May 14 to May 16, 2018, at the Department of Mathematics, Politecnico di Milano.

Organized since 2007, the Meeting on Tomography and Applications constitutes now a representative international forum for the tomographic research community. The meeting provides an opportunity of sharing ideas and having discussions from various viewpoints thanks to the different kinds of expertise ranging from mathematics, computer science, engineering, and physics to medicine and biology. To strengthen the interdisciplinary character of the meeting and to extend its range of applications, the meeting included (for the second time) a special section on neuroscience. Indeed, techniques from tomography such as Magnetic Resonance Imaging (MRI) enable the measurements of both, functional and structural connectivity, and they offer a bridge between the fields that share graph-theoretical methods for modeling and analysis. The meeting was successful, as it provided interesting presentations, extensive discussions, and valuable audience response, contributing in this way to defining new lines of research and to initiating new as well as strengthening of the already existing scientific collaborations.

2. Outline of the talks

In this section we give an overview of the talks given at the meeting.

MAIN LECTURES

- Peter Gritzmann - Technische Universität München

  On Dynamic Discrete Tomography

  ABSTRACT The problem of reconstructing the paths of a set of points over time is considered, where, at each of a finite set of moments in time the current positions of points in space are only accessible through some small number of their X-rays. This particular particle tracking problem, with applications in, e.g., plasma physics, is the basic problem in dynamic discrete tomography. We introduce and analyze various algorithmic models. In particular, we determine the computational complexity of the problem (and its relatives) and derive algorithms that can be used in practice.

This is joint work with Andreas Alpers.

- Antal Nagy - University of Szeged

  Segmenting Head and Neck MR Images

  ABSTRACT Magnetic Resonance Imaging (MRI) is a non-ionizing radiation imaging technique, which gives a high level of information on tissue changing in human body. We present mainly results on MRI organs at risk segmentation in Head and Neck region performed in a current project. We also show liver tumor segmentation and characterization achievements, and discuss the pre- and post-processing techniques, applied in our work.

- Samuli Siltanen - University of Helsinki

  Dynamic Sparse X-ray Tomography

  ABSTRACT In recent years, mathematical methods have enabled three-dimensional medical X-ray imaging using much lower radiation dose than before. One example of products based on such approach is the 3D dental X-ray imaging device called VT, manufactured by KaVo Kerr. The idea is to collect fewer projection images than traditional computerized tomography machines and then use advanced mathematics to reconstruct the tissue from such incomplete data. The idea can be taken further by placing several pairs of X-ray source and detector filming the target from many directions at the same time. This allows in principle recovering the three-dimensional inner structure as a function of time. For example, one could observe the internal organs of a living and un-sedated organism such as a laboratory mouse. Tentative computational results are shown, based on both simulated and measured data. Several mathematical approaches are discussed and compared: generalized level-set method and shearlet-sparsity in spacetime, dimension-reduced Kalman filter, and sparsity-promoting regularization based on optical flow. It is expected that each method performs differently with different dynamic applications.

- Laurent Vuillon - Université de Savoie

  Convexity Concepts for Discrete Tomography

  ABSTRACT In this talk, we focus on discrete convexity concepts for discrete tomography. In fact, the convexity is a usual tool in order to construct geometrical objects which inherit nice mathematical properties. We first survey these properties based on the work of Marcel Berger and on convex geometry. Then, we investigate many notions of discrete convexity and discuss the pertinence of these concepts for discrete tomography problems. Subsequently, we explore these notions for polyominoes and for polycubes, with the goal of adding convexity constraints to discrete tomography in 2D and 3D. In particular, we investigate many examples of convexity properties such as HV-convexity, Q-convexity, 1L-convexity, 2L-convexity and kL-convexity.

Then we explain how to use discrete convexity to reconstruct 2L-convex polyominoes. Finally, we present a catalogue of open convexity problems for discrete tomography approaches.

OTHER TALKS

- Andreas Alpers - Technische Universität München

  Super-Resolution Imaging in Discrete Tomography

  ABSTRACT Super-resolution imaging aims at improving the resolution of an image by enhancing it with other images or data that might have been acquired using different imaging techniques or modalities. In this talk we consider the task of doubling, in each dimension, the resolution of greyscale images of binary objects by fusion with double-resolution tomographic data that have been acquired from two viewing angles. It turns out that this task is polynomial-time solvable if the grey levels have been reliably determined. The problem becomes NP-hard if the grey levels of some pixels come with an error of +-1 or larger. The NP-hardness persists for any larger resolution enhancement factor. This means that noise does not only affect the quality of a reconstructed image but, less expectedly, also the algorithmic tractability of the inverse problem itself.

  This is joint work with Peter Gritzmann.

- Marina Bentivoglio - Università di Verona

  The Challenge of Brain Structural Connectivity

  ABSTRACT Neurons, born to form a social ensemble, need to communicate through connections. Structural connectivity underlies behavioral output. Modeling the brain and its connectivity currently allows the elaboration of large scale data and therefore provides a novel insight in the human brain, leading to novel views on neural circuits working in functional networks. However, there are practical and conceptual gaps between the brain nodes, hubs, edges of connectomics approaches and the data on brain structural connectivity. These gaps need to be highlighted and filled with a constructive cross-disciplinary dialogue. Key issues at the microscale and mesoscale levels versus the macroscale level of brain studies are represented in the white matter by monosynaptic versus polysynaptic connections, crossing trajectories as well as multiple targets of fibers following the same trajectory, the heterogeneity of axon caliber, the organization of branched connections via axon collaterals, and the role of glial cells. In the grey matter, examples are represented by neuronal heterogeneity (of size, molecular regulation, changes over time, neurotransmitter and neuromodulator content, multiplicity of targets, and vulnerability to challenges and disease), the composition of the neuropil and of the synaptic microenvironment, and the relationships between neuronal compartments and glia. Brain pathologies cause connectopathies, but these are emphasized by synaptopathies. The imaging and modeling of connectopathies at the macroscale has a high potential to serve diagnostic and prognostic endeavors, but the unraveling of pathogenetic mechanisms (essential to devise therapeutic strategies) requires efforts at the micro- and mesoscale. Computational views and reconstructions thus need to be reconciled with cardinal concepts of structural connectivity in the grey and white matter for a comprehensive, effective approach to brain wiring, functional output, and alterations in disease.

- Giulia Colacicco - CWI Amsterdam

  Challenges in Adaptive Acquisition of Tomography Data

  ABSTRACT In May 2017, the FleX-Ray lab was established by the Computational Imaging group at CWI, in collaboration with partners XRE, Nikhef, and ASI. The lab is dedicated to advancements in new algorithmic techniques for 3D imaging, and combines an advanced, flexible CT scanner with high-performance computing facilities that can directly interface with the system. One of the main features of the custom-built FleX-Ray CT scanner is the large freedom of placement and movement of the X-ray source, the sample and the detector. It allows to emulate many different experimental setups, with different scanning trajectories, tailored to various types and sizes of objects. Moreover, it is possible to reliably scan both static 3D and dynamic 3D (i.e. 4D) objects. In the latter case, the behavior and the movement of the object are unknown a priori. By adaptively changing the trajectory of both the source and the detector in response to the data that has already been collected, the quality of the reconstructions can in principle be improved by optimizing the trajectory for the specific characteristic of the sample. However, designing an accurate and efficient reconstruction process for arbitrary source/detector geometries comes with many challenges. One of the elements that has to be taken into account is the flat-field acquisition: the image acquired at the detector when there is no sample present. Flat-fields describe the shape of the X-ray beam and imperfections of the detector, and are used to preprocess the pixel-to-pixel sensitivity during the acquisition of the data. In standard CT scans, the flat-field is acquired once before the start of the imaging procedure. With an adaptive trajectory, it is no longer possible to use a flat-field that was previously acquired. In this talk we will introduce the main concepts of adaptive tomography that are being developed in the FleX-Ray lab. We will then present the problem of computationally recovering the flat-field in the adaptive setting.

- Maria M. Del Viva - Università di Firenze

  Role of the Cost of Plasticity in Determining the Features of Fast Vision in Humans

  ABSTRACT Several studies have demonstrated the usefulness of general principles of computational efficiency and maximum information preservation in predicting even rather detailed properties of early vision. While all these studies have deeply examined the efficiency of the computation involved in the processing that actually occurs during the early visual analysis, not much attention has been devoted to the issue of the complexity of the computation required to determine the base ingredients of that processing themselves (neural Receptive Fields). Indeed, some of those algorithms require rather complex calculations in order to determine the shape of the RFs. Considering the plasticity of the visual systems, one might expect that the algorithms employed by the visual system should not only be economical to execute, but also reasonably economical to set up, and to update when adapting to varying external conditions. In this regards, it is an interesting question whether there are examples where the visual system has made a choice that is suboptimal from the point of view of the run-time performance, but lends to easier and more efficient updates and improvement. In this work we present results of a psychophysical experiment that appears to be such an example. We start from a model of early vision, where the general principle of computational optimality takes the form of a maximization of transferred entropy within a limited bandwidth and from a fixed, finite number of discrete patterns, that are assumed to be the only information recognized by the system. This approach

captures very well the problem faced by a system with finite computational resources, and has proved to be very effective in practice, in describing the actual human performance in fast vision in a number of situations. In addition, it lends very well to comparing the properties of mathematically optimal solutions to approximate, and therefore sub-optimal, solutions that are easier to compute and update. More specifically, the optimality condition that is imposed on the set of RF in this approach, can be formulated as a case of a class of well-known problems that go under the name of "knapsack problems". These problems admit exact numerical solutions, that in the general case are rather expensive to compute, and simpler approximate solutions that are slightly less optimal, as the one that has been heuristically adopted in our paper published in PLoS ONE 8(7), 2013. We have found that application of these approaches to the extraction of optimal visual patterns lead to similar but nonetheless clearly distinguishable solutions, raising the interesting question of which of the two better describes the actual performance of fast vision in human subjects. By performing psychophysical experiments we found clear evidence that the actual performance of human vision is in agreement with the simpler approximate solution rather than the mathematical optimum. While the latter is slightly better from the point of view of computational efficiency of the image analysis, the simpler solution is much easier to determine and update in case of the need to adapt to changes of the external conditions. This experimental result thus seems to provide the evidence for a well-defined role of the "cost of plasticity", in shaping the features of the visual system.

- Paolo Finotelli - Politecnico di Milano

  Introduction to the Neuroscientific Section

  ABSTRACT This talk has the purpose of providing some basic notions from Neuroscience, in order to introduce the audience to the contributions of the neuroscience section of this meeting. Firstly, some of the basic neurobiology behind the nervous system will be covered. Then, we discuss how Graph Theory could be a useful tool in Neuroscience and in some related applications. Finally, a recent model for evaluating the functional connectivity in a cerebral network will be introduced.

- Caroline Garcia Forlim - University Medical Center Hamburg

  Neuroimaging and Brain Networks

  ABSTRACT Brain imaging plays a central role in modern Neuroscience as the window into the brain. The most used neuroimaging are MRI, fMRI, EEG, MEG, PET, DTI, among others providing measures of the structure and functionality of the brain. Each of them examines aspects of the brain at different spatial and temporal resolutions. Here the focus is of the discussion is on the main characteristics of MRI, fMRI, EEG and DTI as well as their advantages and disadvantages. We also present how brain networks can be extracted from the techniques above. Brain networks consist of structurally or functionally connected regions. Disruption in networks were found in many diseases, as schizophrenia, epilepsy, Alzheimer, ASD, depression, dementia etc. Finally we present results of graph analysis applied to brain networks of schizophrenic patients.

- Gloria Menegaz - Università di Verona

  A Multi-view Perspective of Neuroimaging

  ABSTRACT Brain imaging has many facets. Diffusion MRI (dMRI) allows for a non-invasive in-vivo virtual neuroanatomy, capturing the white matter (WM) wiring of the brain network.

Functional neuroimaging captures the activity of brain regions following different paradigms, ranging from neurophysiological activity (EEG) to perfusion including blood-oxigen-level dependent contrast imaging (fMRI) and arterial spin labelling (ASL), just to mention a few. Such richness of information provides a multi-view and multi-scale picture of the brain structure and function, from tissue microstructure to connectivity networks. This lecture provides an overview of the field as well as a closer look at some specific themes, e.g., signal modeling in dMRI and microstructure-informed modeling of connectivity (structural and functional) networks.

- Nicolas Normand - Université de Nantes

  Vandermonde-based Tomography Algorithms in Periodic and Non-periodic Discrete Spaces

  ABSTRACT Algorithms for discrete Radon transforms usually display quite different approaches in periodic and non-periodic spaces. Inversion of the Mojette transform (MT), a non-periodic example, can use corner-based or geometry-based algorithms. By contrast the Finite Radon Transform (FRT), the periodic example most similar to the Mojette Transform, can use exact back-projection, de-ghosting, Fourier and generalised Fourier transforms. Recently, a bridge between these methods was established by converting a non-periodic set of projections into a periodic one allowing to reconstruct Mojette projection data using Finite Radon Transform tools. This presentation focuses on a new approach for tomographic reconstruction that is based on the Vandermonde structure of discrete Radon transforms. We show that Bjrck's algorithm for solving Vandermonde systems can be adapted to tomographic problems in both periodic and non-periodic spaces by the use of the proper operators applied to each row of a matrix of projection data or, equivalently, to a matrix of their Fourier coefficients. The link with Katz's criterion on uniqueness of reconstruction will be discussed.

- Alice Presenti - University of Antwerp

  A CAD Projector for X-ray Polychromatic Projection-based Inspection

  ABSTRACT 3D Computed Tomography is increasingly used in inspection and metrology to measure the deviation of the acquired geometry from the reference geometry, usually defined in a Computer Aided Design (CAD) model. However, the conventional CAD based X-ray inspection workflow can suffer from substantial error propagation. This can be avoided by coupling the 3D inspection back to the projection space. To this aim, we present a CAD projector for the ASTRA Toolbox, an efficient tool capable of simulating poly-energetic X-ray radiographs directly form CAD data in STL format, and integrated with a 3D registration framework that estimates the CAD model position from few-view projection data.

- Alice Presenti - University of Antwerp

  Graph Model Simulation of Human Brains Functional Activity

  ABSTRACT It is commonly accepted that the various parts of the human brain interact as a network both at a macroscopical and microscopical level. Recently, different network models have been proposed to mime the brain behavior both at resting state and during tasks: our study concerns one of those models that tries to combine both the physical and the functional connectivity of the brain and also includes a time related variable that spans over the whole life period. We provide evidence of the soundness of the model by means of an artificial dataset based on the existing literature concerning the active areas at resting state. Furthermore, we consider Ruzicka similarity measure in order to stress the predictive capability of the model. Some network statistics are finally provided.

- Nathanael Six - University of Antwerp

  Discrete Reconstruction from Polychromatic X-ray Projection Data

  ABSTRACT Discrete tomographic reconstruction (e.g. DART) can suffer heavily from the effects of beam hardening. This is due to the double effect of the polychromatic source on these techniques: on the one hand, beam hardening artefacts such as cupping and streaks appear and on the other hand, the mismatch between the assumed linear model and the real non-linear acquisition leads to wrongly assumed grey values. Discrete reconstruction techniques are, however, of great interest as they can generate reconstructions from a low sampled projection space. By introducing a non-linear forward model in the reconstruction, discrete tomography on datasets from polychromatic sources becomes possible. The drawbacks are the need of extra prior knowledge on the X-ray source and a larger computation time per iteration. We present a method to improve DARTs behavior in this setting. On simulated data, the reconstructions no longer suffer from beam hardening artefacts, while retaining DARTs ability to generate accurate reconstructions from undersampled data.

- Lama Tarsissi - Polytechnique Sophia Antipolis, Nice

  New Perspectives in the Reconstruction of Convex Polyominoes from Orthogonal Projections

  ABSTRACT The family of (digitally) convex polyominoes, that are the discrete counterpart of Euclidean convex sets, combines the natural constraints of convexity and connectedness. Several years ago, many researchers in this community tried to study their reconstruction. In this talk, we use some results by Brlek et al., which allow to express digital convexity by the properties of the words encoding the boundary word of the polyomino. We give some examples to show that, in order to maintain the convexity, the addition of one point or two points imposes the inclusion of other points in the neighborhood areas.

- Stefano Tebaldini - Politecnico di Milano

  Three-dimensional Radar Imaging of Distributed Media

  ABSTRACT Synthetic Aperture Radar (SAR) Tomography (TomoSAR) is a microwave imaging technology to recover the 3D structure of the illuminated scene by flying a Radar sensor along multiple trajectories. At microwave regime, electromagnetic waves are capable of penetrating into natural media that are non-transparent at optical frequencies, for example vegetation, snow, ice, and sand. This feature makes TomoSAR sensitive to the vertical structure of those media, hence providing a substantial advantage over optical sensors. The downside is that TomoSAR signal processing involves a number of challenging aspects as compared to conventional 2D SAR focusing, such as: 3D migration, focusing in the presence of propagation velocity variations, and sub-wavelength data-based retrieval of platform position. The aim of this talk is to present different aspects pertinent to tomographic SAR imaging and its applications, such as: basic imaging principles, advanced signal processing, polarimetry and tomography, added value for forestry, snow-pack and glacier remote sensing, and possibilities for spaceborne tomography.

- Robert Tijdeman - Leiden University

  Algorithms for Fast Reconstruction in Discrete Tomography

  ABSTRACT We present an algorithm that for any given rectangle A in $\mathbb{Z}^2$ and set of primitive directions D enables us to compute the values of any real function f on A outside the convex hull of the union of the switching components in linear time from its line sums in the directions of D. In particular, the algorithm enables us to reconstruct f completely if there are no switching components. We present a simpler algorithm in case the directions satisfy some monotonicity condition. Finally we suggest how to choose the directions so that only a small number of them is needed to reconstruct f.
  This is joint work with Silvia Pagani.

- Nicola Viganò - CWI Amsterdam

  A Tomography Approach for the Quantitative Scene Reconstruction from Light-field Images

  ABSTRACT Portable plenoptic cameras have recently become increasingly popular and accessible. An attractive feature of these cameras is that they provide a wide palette of computational photography opportunities which do not exist with traditional cameras. These include post-acquisition refocusing and depth estimation. To manipulate the acquired light-fields, current computational methods parametrize the ray geometry inside the plenoptic camera. This parametrization, together with some common approximations, can lead to errors in the estimation of object sizes and positions. In this talk, we present a parametrization that can offer correct reconstruction of object sizes and leads to the accurate estimation of their distances from the camera. This is obtained by showing that light-field photography problems can be formulated as cone-beam tomography problems with limited-angle data. The strong connection with tomographic problems is then also used to critically and quantitatively analyze the parametrization impact on image refocusing, depth estimation and volumetric reconstructions. Finally, we present and discuss a set of numerical examples to show the impact of the developed methods on the quantitative estimation of object sizes and distances.

3. Papers in this Special Issue

After a thorough refereing process, 7 papers were selected for this special issue. They provide a good insight into both theoretical and applied aspects of tomography and neuroscience.

• Quinten Beirinckx, Gabriel Ramos-Llordén, Ben Jeurissen, Dirk H.J. Poot, Paul M. Parizel, Marleen Verhoye, Jan Sijbers, Arnold J. den Dekker, *Joint Maximum Likelihood Estimation of Motion and T1 Parameters from Magnetic Resonance Images in a Super-resolution Framework: a Aimulation Study*.

This research concerns the estimation of the material distribution inside a body-tissue using low resolution MRI images: for several uses the standard process that detects this distribution with high level accuracy is sometimes too much time consuming. Here, the authors use a previous faster estimation strategy and present a simulation study with potential for earlier diagnosis of various brain diseases including multiple sclerosis, epilepsy and Alzheimers disease. This strategy allows also an estimation of the motion of the material, that, in this artificial data simulation, turns out to produce a more accurate output.

• Gábor Lékó and Péter Balázs, *Scale Invariance in Projection Selection Using Binary Tomography.*

In this paper the authors propose strategies to reduce the amount of data needed to select the most informative projection angles for binary tomographic reconstructions. The experiments show that the images can be downscaled to levels that are still as informative as the original one for projection selection purposes, and the number of beam rays can be also lowered for the projection acquisition. Moreover perimetric complexity is used to automatize the resolution reduction process and to choose the proper number of projections.

• Marinus J. Lagerwerfy, Willem Jan Palenstijn, Folkert Bleichrodt and K. Joost Batenburg, *An Efficient Interpolation Approach for Exploring the Parameter Space of Regularized Tomography Algorithms.*

The paper presents a way to estimate the optimal regularization parameter from a set of reconstructed images, each with a different regularization parameter. The choice for this parameter depends on many properties of the problem such as the measured data and its noise level, or the reconstruction method and its implementation. The topic of regularization is an old but still relevant one, as it is far from trivial in practice. Differently from previous standard approaches, the authors propose a computationally efficient algorithm to explore the regularization parameter space: first they compute a relatively small number of rough reconstructions for a sparse sampling of the regularization parameters and subsequently they obtain a fast approximation of the reconstructed image for the other parameter values.

• Gloria Menegaz, Claudio Tomazzoli, Matteo Cristani, Ilaria Boscolo Galazzo, Silvia Francesca Storti, *Characterising Functional Brain Connectivity as Social Network: the Transtopic Centrality Index.*

Graph theory and network science can be profitably exploited for modeling the brain architecture as a set of nodes connected by edges. In recent years, the emerging discipline called Social Network Analysis (SNA) has increasingly adopted the use of graphs as network models, where the nodes are qualified by their capacity of diffusing a message with a certain semantics.

The paper focuses on two main issues: social networks and functional brain networks. In particular, it is emphasized that task-driven measures of node centrality represent the link that joins SNA to brain connectivity.

The proposed model for SNA represents a simplification of a multi-layer network where inter-layer links are not modelled and for which a simple combination of closeness centrality values (transtopic centrality) is proposed as means to stress the importance of a node in forecasting a given type of message through the network. These are referred to as *vector-valued* graph.

Then, through an experimental study, the question is investigated whether using vector-valued graphs can bring new insights even to brain Functional Connectivity (FC). This is considered under the assumption that layers corresponding to different tasks are independent. It represents a first simple step towards a better understanding of what kind of added values non-interconnected network models would bring to FC analysis, in view of possible generalisation of the properties of interest (such as closeness centrality) to interconnected multi-layer graphs.

• Luca Presotto, *A L_1 Minimization Strategy for Robust Joint Activity and Attenuation Estimation in Positron Emission Tomography*.

The author proposes an interesting study about a computational approach for jointly estimating the attenuation and activity maps from PET data. At the same time, he also detects the attenuation of the $511\ KeV$ photon. The approach tackles the strong uncertainty of the attenuation map due to patient motion in sequential systems or to intrinsic limitation of the second modality, by enforcing strong regularization. A final simulation study shows that the proposed approach indeed leads to accurate estimations of the activity and a desirable level of detail in the attenuation maps.

• Léonard Turpin, Stéphane Roux, Olivier Caty, Sébastien Denneulin, *A Phase Field Approach to Limited-angle Tomographic Reconstruction*.

A lot of tomographic reconstruction commercial software is based on Filtered Back-Projection (FBP) algorithm, where projection angles have to sample $360°$ (or $180°$ for a parallel beam) with an equi-angular spacing. However, in case of limited angle tomography, FBP algorithms could still be considered from an iterative point of view, which leads to the Iterative Reconstruction-Reprojection (IRR) method.

In IRR, an FBP reconstruction is performed initially based on arbitrary projection data (e.g. blank image) for missing angles. The reconstructed volume is then filtered so as to get rid of the nonphysical data (such as negative absorption coefficients). In this step it is important to take into account possible a priori information, which can be considered as a form of regularization that provides a more likely substitute for the missing data and speeds up convergence.

For complex materials and industrial parts, the regularization is often based on the homogeneous phases composing the object of interest. The present article proposes an original regularization approach based on a phase field model. The sample chosen to illustrate the analysis is a Ceramic Matrix Composite (CMC), where matrix and fibers are made of the same material, so that, in order to distinguish the texture, an excellent quality tomography is required. Since the chemical species are light elements, the X-ray absorption is low and gives rise to a significant beam-hardening (BH). The composite sample is placed in a mechanical testing device which presents two columns on the side of the sample that cross the beam line during the tomographic acquisition, so that angular data are missing to perform the reconstruction. The IRR method is used to alleviate the difficulty of these missing data, and BH corrections and a rich prior filter (based on phase-field approach) are employed to extract an accurate 3D reconstruction.

• Sara Brunetti, Paolo Dulio, Carla Peri, *Uniqueness Results for Grey Scale Digital Images*.

In this paper the authors address the problem of reconstructing digital images with finitely many grey levels from the knowledge of their X-rays in a given finite set of lattice directions. The main result provides sets of $2p$ ($p \geq 3$) lattice directions which uniquely determine images with p grey levels, contained in a finite lattice grid. This extends previous uniqueness results for binary images.

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