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Contents

Advanced polarimetric tissue characterization across scales: from blocks to *in vivo* imaging

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Abstract

Tissue analysis with polarized and complex structured light utilizes the vector nature of optical field to generate intrinsic contrast linked to tissue microstructure. Hyperspectral imaging adds functional and biochemical sensitivity based on wavelength-dependent signatures. Bringing these modalities together enables multidimensional, label-free tissue characterization for different spatial scales, supporting both *in vivo* functional assessment and non-destructive analysis of excised specimens.

In this talk, I will present hyperspectral polarimetric imaging as an effective approach for probing biotissues, using two complementary measurement strategies. A high resolution full Stokes polarimetric implementation is aimed at detailed microscopic assessment of histological tissue blocks, whereas a compact camera-based hyperspectral polarization approach is optimized for practical, wide-area *in vivo* imaging. Together, they provide polarization-derived markers that augment spectral contrast and improve sensitivity for structural and functional sensing.

The work is supported by the EU Horizon Europe EIC Pathfinder Open Research and Innovation Programme, OPTIPATH project (Grant Agreement No. 101185769).

Solving inverse problems in image processing using unrolled algorithms

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Abstract

We developed deep unroll networks which are a hybrid AI powerful tool intertwining optimization and learning to solve inverse problems in signal and image processing. Proposed networks are highly interpretable and by physics-informing them, we reduced the required training dataset size and so the training time.
While the majority of recent works on algorithm unrolling has focused on learning the image prior (i.e. the regularisation term), we proposed to carefully design the data fidelity term to account for the various degradations affecting the acquired data (e.g. noise, quantization, background signal).
We explored the idea of learning a weighted least squares data fidelity term to better adapt to various types of noise in inverse problems. In addition, we plugged into it more advanced (learned) priors inspired by plug-and-play methods. The overall methodology consists in an end-to-end training approach combining a weight estimation module with an unrolled algorithm. This results in a lightweight and highly interpretable architecture.
The effectiveness of our approach is demonstrated in the context of image deconvolution involving intricated noises.

References

[1] Abhijit Singh, Emmanuel Soubies, Caroline Chaux, Learning Weighted Least Squares Data Term for Poisson Image Deconvolution, ICASSP, Hyderabad, India, 6-11 Apr. 2025. https://hal.science/hal-04887464

Motion Reconstruction from Diffraction Tomography Data

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Abstract

In tomographic imaging, we usually rely on being able to illuminate the sample from multiple directions to gather enough information for a three-dimensional reconstruction. Especially for small objects, it is, however, difficult to ensure that the sample remains still during the illuminations without fixating and thereby typically modifying it.

To observe such objects in a more natural environment, one can use optical or acoustical tweezers which hold the sample with the corresponding kind of forces into place. Moreover, by tuning these forces, it is even possible to induce a rotation of the object so that we can observe it with a fixed incident wave in multiple different orientation states. Nevertheless, this comes at a certain price: the strength of the acting forces depends on the physical properties of the sample and is thus unknown.

We therefore face the question whether it is possible to read off from the scattering data of the object its current motion so that we can recover for every measurement time the actual position and orientation of the sample and thus reduce the reconstruction problem to the classical inverse scattering problem.

We would like to discuss this issue in the case of diffraction tomography, meaning that we linearise the wave equation by using the Born approximation, with interferometric measurement data and show that the determination of the movement of the object is at least for generic (not too symmetric) objects always possible and provide an explicit reconstruction algorithm.

The talk is based on the following articles:

[1] P. Elbau and D. Schmutz, "Uniqueness of Angular Velocity Reconstruction in Parallel-Beam and Diffraction Tomography", ArXiv 2510.18829, 2025.

[2] M. Quellmalz, P. Elbau, O. Scherzer, and G. Steidl, "Motion detection in diffraction tomography by common circle methods", Mathematics of Computation 93, pages 747–784, 2024.

[3] P. Elbau, M. Ritsch-Marte, O. Scherzer, and D. Schmutz, "Motion Reconstruction for Optical Tomography of Trapped Objects", Inverse Problems 36.4, 044004, 2020.

How “vibe-coding” helps build a new-generation Monte Carlo simulator over a weekend

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Abstract

Diffuse optical tomography (DOT) relies on efficient forward modeling and model-based image reconstruction to detect deeply embedded abnormalities in turbid media such as human tissues. While the diffusion equation (DE) remains the most widely used forward model due to its speed and deterministic output, Monte Carlo (MC) methods solving the radiative transfer equation (RTE) have gained increasing adoption for their ability to handle complex media where DE fails. In particular, mesh-based MC (MMC) has become increasingly used in routine DOT analysis, owing to GPU acceleration and the capacity to represent sophisticated anatomies via mesh models. Recently, we further advanced MMC by leveraging graphics ray-tracing (RT) pipelines and emerging RT-core hardware, achieving 1.5× to 4.5× additional speedup.

Here we report a new-generation RT-core accelerated MMC (RT-MMC) photon simulator rapidly prototyped through human-artificial intelligence (AI) collaboration. By uploading our manuscript describing the RT-MMC algorithm, including the simulation workflow diagram, to an AI coding agent (Claude.ai, Opus 4.6, Anthropic), we re-implemented the full algorithm using the Vulkan ray-tracing framework in only a few prompts. We further instructed the agent to implement an RT-core accelerated surface-based MC algorithm featuring automatic shape-based surface mesh generation and constructive solid geometry (CSG) ray-marching with a state-vector to efficiently track overlapping regions and perform quantitative simulations. This eliminates the need for manual mesh generation – a major bottleneck of public MMC simulators. Additionally, the agent was instructed to compute the principal curvatures at the surface nodes, enabling accurate reflection/transmission modeling for optical components, including lenses. The entire simulator was completed in two days, producing quantitatively accurate 3-D light transport results. With human guidance, the AI agent also performed GPU optimization, achieving simulation speeds comparable to or exceeding our manually implemented NVIDIA-only RT-MMC.

This work demonstrates that AI coding agents can comprehend sophisticated computational algorithms from textual and graphical descriptions and convert them into high-quality optimized code. These powerful tools are expected to greatly accelerate the development of open-source DOT computational software.

Time-Domain Diffuse Optical Imaging in Biomedical Tissues

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Abstract

Diffuse optical imaging is a powerful methodology for quantifying and mapping the optical properties of biological tissues and has found application in diverse areas, including optical mammography, functional neuroimaging, and molecular imaging. Several strategies can be adopted for the characterization of highly scattering (diffusive) media, all relying on spatial and/or temporal modulation of the illumination and on appropriate detection schemes. The principal modalities comprise Continuous-Wave (CW), Time-Resolved or Time-Domain (TD), Frequency-Domain (FD), and Spatial Frequency-Domain Imaging (SFDI).

Among these approaches, time-domain techniques possess a distinctive advantage arising from their ability to directly measure the distribution of photon time-of-flight through tissue. This temporal information is tightly linked to photon pathlength statistics and, consequently, impacts both achievable spatial resolution and penetration depth.

In this work, we provide an overview of the fundamental principles of time-domain diffuse optical imaging and discuss their implementation in Diffuse Optical Tomography (DOT). Furthermore, we examine the role of structured or patterned illumination and detection within the framework of single-pixel imaging, and we outline prospective developments and future directions for this imaging modality.

A bilinear inverse problem with forward operator inaccuracy applied to diffuse optical tomography

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Abstract

Linear inverse problems are common in real-world applications from industry to medical imaging, but handling inaccuracies in the associated forward operators is a relatively unstudied problem. In this work, we assume that we have a set of candidate forward operator matrices and suggest principal component analysis for modeling their variation from the mean. We combine the original linear problem with the included forward operator inaccuracy into a bilinear tensor inverse problem and present two optimization algorithms and Gibbs sampling for approximately solving the problem. As a real-world test case, we apply the algorithms to account for the inaccuracy that is present in the sensitivity profiles or Jacobian matrices in diffuse optical tomography when an atlas-based model of the head anatomy is used instead of the subject's own anatomical model. We report visual and numerical improvements in the spatial localization and contrast-to-noise-ratio in reconstructions of simulated brain activity.

Projections for handling uncertainties and enabling localization in diffuse optical tomography

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Abstract

This talk presents a projection-based technique to mitigate the impact of modeling errors related to domain truncation, changes in the coupling coefficients at the optode-object interfaces, and misspecified optical parameters of different tissue types in diffuse optical tomography. The method considers the primary Jacobian matrix of the forward map, linking the primary unknown, i.e. the voxelized absorption change in the region of interest, to the optode measurements, as well as the nuisance Jacobians that do the same for the parameters of secondary interest. For mismodeled coupling coefficients or domain truncation, the method projects the linearized forward model defined by the primary Jacobian onto the orthogonal complement of the range of a nuisance Jacobian, or onto the orthogonal complement of the span of a number of first left singular vectors for the nuisance Jacobian that has been weighted to account for prior information on the measurement setup. In case of a misspecified optical parameter for some tissue type, the nullspace of the utilized orthogonal projection is instead defined to be the span of first left singular vectors for a (weighted) difference of two primary Jacobians evaluated at two different levels for the considered tissue-wise optical parameter. The actual reconstruction is formed by applying Bayesian inversion with Gaussian prior and additive noise to the projected linearized forward model. We verify the method on data obtained via Monte Carlo simulations of the radiative transfer equation on a voxelized head anatomy of a neonate.

Machine learning enhanced image reconstruction in optical tomography using Monte Carlo method for light transport

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Abstract

Optical tomography is an imaging method in which optical properties of an imaged target are reconstructed from light transport measurements made on the boundary of the target. In this work, we are considering the absolute image reconstruction problem of absorption and scattering. When solving this inverse problem numerically, the light transport inside the imaging domain needs to be modelled, using, for example, the radiative transfer equation. In this work, the Monte Carlo method of light transport is used to approximate the solution of the radiative transfer equation, and the search directions of a minimization algorithm used in solving the inverse problem.

The stochastic nature of the Monte Carlo model introduces stochastic noise to the forward model and the search direction while solving the inverse problem. The amount of stochastic noise is proportional to the number of photon packets used in the simulations, but simulating a large number of photon packets comes with a computational cost. In this work, we propose using machine learning to compensate for the stochastic noise in optical tomography image reconstruction. More specifically, in the proposed method, convolutional neural networks are used to correct the stochastic Gauss-Newton update. The proposed method is evaluated with numerical simulations.

Photoacoustic and Ultrasound Tomography for Breast Imaging

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Abstract

New high-resolution, three-dimensional imaging techniques are being developed that probe the breast without delivering harmful radiation. In particular, photoacoustic tomography (PAT) and ultrasound tomography (UST) promise to give access to high-quality images of tissue parameters with important diagnostic value such as optical absorption, blood oxygen saturation, sound speed, acoustic density and acoustic attenuation. However, the involved inverse problems are very challenging from an experimental, mathematical and computational perspective. In this talk, we want to give an overview of these challenges and illustrate them using data from a clinical prototype scanner for combined PAT and UST. We show results from different experimental phantoms, healthy volunteers and breast cancer patients from two ongoing clinical feasibility studies.

Inverse Rytov series for optical tomography

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Abstract

Since severly ill-posed inverse problems have to be solved for optical tomography, the number of practical inversion schemes is limited. The (first) Rytov approximation is often employed to solve such inverse problems.

The (first) Rytov approximation approximates a nonlinear inverse problem to a linear inverse problem. Recently, it was shown that nonlinear terms can be taken into account with the inverse Rytov series (M. Machida, Inverse Problems **39**, 105012 (2023)).

In this talk, I will explain the inverse Rytov series and how it can be used for optical tomography.

Ultrasound-modulated diffuse optical tomography in the Bayesian framework

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Abstract

Ultrasound-modulated diffuse optical tomography (US-DOT) estimates spatial distributions of optical parameters, using an acousto-optic effect in which near-infrared light is modulated by a focused ultrasound. The use of an acoustic modulation enables an increased resolution when compared to the conventional diffuse optical tomography.

In this work, we formulate US-DOT image reconstruction in a Bayesian framework and consider non-stationary estimation of tissue optical parameters. We compute maximum-a-posteriori estimates and approximate posterior covariances to obtain uncertainty intervals for the reconstructed parameters. These estimates are evaluated across multiple imaging scenarios, varying the location, density, and size of the ultrasound focus, as well as boundary source and detector configurations. For non-stationary estimation, we apply two time-varying models: random walk and vector autoregression. The results show that state estimation significantly improves reconstruction of non-stationary targets in US-DOT, even with relatively simple temporal models.

Optical tomography - technology and applications in neuroimaging

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Abstract

Optical tomography is a medical imaging method based on the absorption and scatter of visible red and near-infrared light, especially sensitive to oxygenated and deoxygenated hemoglobin (HbO_2 and HbR, respectively). Proposed applications include functional neuroimaging, which can include the imaging of hemodynamic changes related to neuronal activity in neuroscience as well as the imaging of clinically relevant parameters including biomarkers derived from hemoglobin responses either in rest or during tasks. Advantages of the method include the relative comfort of the measumements, some liberty for subject movement, multimodal compatibility, availability of wearable and wireless implementations, good infant tolerance, relatively low cost, and absence of the need for special environments such as a magnetically shielded room.

In this talk, I will describe our approach to optical tomography in functional neuroimaging, including the experimental setup, data analysis pipeline, and go through results of our recent practical application studies which include neuroimaging of pediatric populations and multimodal neuroimaging. Biomarkers based on optical and multimodal measurements could predict future health problems. We are currently investigating listening effort in healthy and hearing-impaired children and the detection of brain lesions related to stroke, and monitoring of the effects of treatment.

There are still significant challenges before DOT can become an easy-to-use neuroimaging method for routine neuroscientific and clinical applications. Current trends in instrumentation are concentrated around wearable systems. Our research is presently focused on expanding the field of view of optical neuroimaging to areas in the sulci via improvements in modeling accuracy and instrument signal-to-noise ratio, and investigating analysis methods for multimodal functional neuroimaging data.

A wearable CMOS transceiver for time-domain diffuse optics

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Abstract

Time-domain diffuse optics (TDDO) is promising tool to characterize turbid media like biological tissues. In TDDO, optical properties of the media can be evaluated by the distribution of the time-of-flight (DTOF) of the back scattered photons. In TDDO, short optical pulses (100 ps) are transmitted to tissue and photodetectors with time interval measurement units measure DTOF of backscattered photons. The development of CMOS technologies has made it possible to integrate all main components, laser drivers, single-photon avalanche diodes (SPAD) and time-to-digital converters (TDCs) into the same CMOS chip so that a small-sized wearable device can be fabricated.[1]

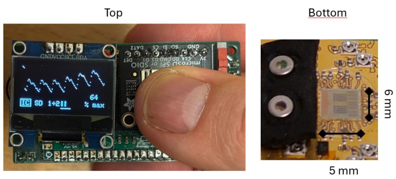

Figure 1: A CMOS transceiver.

The fabricated wearable prototype based on the CMOS transceiver is shown in Fig. 1 and it consists of a laserdiode driver and 8x32 SPAD array with 32 TDCs to measure time-of-arrivals of photons. The proposed prototype achieved a sampling rate of 500 Hz when the PPG signal was measured from the finger.

References

[1] E. Avanzi et al., "Compact Time-Domain Diffuse Optics System Based on CMOS Technologies for Fast Acquisitions of Heartbeat-Induced Absorption Changes," in IEEE Sensors Journal, vol. 24, no. 23, pp. 38912-38921, 1 Dec.1, 2024

Monte Carlo Simulation of Time- and Frequency-Domain Sensitivity Profiles in Optical Tomography

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Abstract

In optical tomography (OT), measurements can be acquired using continuous-wave (CW), time-domain (TD), or frequency-domain (FD) systems. Among these, the TD and FD modalities provide time-resolved information that enables the simultaneous reconstruction of absorption and scattering properties of the medium. Reconstruction techniques typically rely on linearising the relationship between the measurements and changes in the optical parameters. The linearisation is obtained via the Fréchet derivative of the forward model, also referred to as the sensitivity profile, and its finite-dimensional representation as the Jacobian matrix. In OT, the forward problem of light transport is commonly modelled using the radiative transfer equation (RTE), for which the Monte Carlo (MC) method is widely regarded as the gold-standard numerical solver due to its flexibility in handling complex optical systems.

In this talk, I present recent work on computing absorption and scattering sensitivities for TD and FD measurements and on implementing these capabilities in the Monte Carlo eXtreme (MCX; www.mcx.space) software. I derive the MC estimates for the derivatives and compare the resulting sensitivity profiles with those obtained from the diffusion approximation of the RTE using the finite element method. In addition, I discuss the effect of incorporating a more realistic detector model that limits the range of exit angles at which photons leaving the medium can be detected.

Utilising spatial and temporal modulation in time-domain diffuse optical tomography

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Abstract

Diffuse optical tomography (DOT) is a non-invasive imaging technique that utilises visible and near-infrared light to study the structural and functional properties of biological tissues. It has potential applications in medical imaging, such as functional brain studies, breast cancer imaging, and small animal imaging. Among the various modalities of DOT, such as continuous-wave and intensity-modulated DOT, time-domain DOT (TD-DOT) provides the richest information. However, modeling and image reconstruction with full time-resolved TD-DOT data is computationally expensive. Numerous data transformation and structured illumination techniques have been developed to address the challenge of compressing data without compromising reconstruction quality. In this work, we study the use of spatial and temporal modulation. Temporal modulation is implemented using a truncated Fourier-series approximation with different numbers of modulation frequencies, while spatial modulation is implemented using Hadamard patterns both for illuminations and detections. The approach is evaluated using numerical simulations and experiments. The results demonstrate the influence of the number of Fourier frequencies and the number and complexity of Hadamard patterns on image reconstruction.

Realistic Simulated Database for Near-Infrared Fluorescence Diffuse Optical Tomography

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Abstract

We present a large-scale, modular simulation framework for generating reproducible Fluorescence Diffuse Optical Tomography (fDOT) datasets spanning the NIR-I (700–900 nm) to NIR-II (900–1800 nm) spectral windows in murine models. The framework addresses the growing need for standardized benchmarks in fDOT, particularly as interest shifts toward NIR-II imaging, which offers reduced scattering, increased penetration depth, and improved spatial resolution.

Progress in this area remains limited by challenges in forward modeling, data processing, and inverse reconstruction. In addition, the emergence of Artificial Intelligence (AI) methods in optical tomography requires large, diverse, and well-characterized datasets for training and validation. The absence of open and reproducible databases currently restricts fair comparison between competing methodologies.

To overcome these limitations, we construct a large simulated database using a fully modular pipeline that separates geometry generation, optical property assignment, forward problem solution, and post-processing. Geometric variability is ensured through both parametric shape definitions and elastic deformation models for realistic phantoms. The database generation code will be released to promote reproducibility and collaborative development.

Inverse scattering with entangled photons

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Abstract

We consider the quantum field theory for a scalar model of the electromagnetic field interacting with a system of two-level atoms. In this setting, we show that it is possible to uniquely determine the density of atoms from measurements of the source to solution map for a system of nonlocal partial differential equations, which describe the scattering of a two-photon state from the atoms. The required measurements involve correlating the outputs of a point detector with an integrating detector, thereby exploiting information about the entanglement of the photons. This is joint work with Matti Lassas, Medet Nursultanov and Lauri Oksanen.

Time-domain and continuous-wave diffuse optical tomography setups at the OPUS laboratory

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Abstract

In this talk we present the recent developments of time-domain and continuous-wave diffuse optical tomography setups in Biomedical Optical Imaging and Ultrasound (OPUS) laboratory at Department of Technical Physics, University of Eastern Finland. For the systems, we describe the measurement equipment, phantom preparation, and data acquisition process. In addition, data processing and its preparation for image reconstruction is discussed. Examples of measurements and image reconstructions from both setups are shown.

Photoacoustic Imaging for Opto-Mechanical Characterization of the Intervertebral Disc

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Abstract

The intervertebral disc (IVD) undergoes degeneration, resulting in a reduction in its water content and degenerative diseases. Quantitative photoacoustic imaging is introduced here as a method to quantify chromophore content and evaluate the state of the IVD.

In the present work[1], first we built a digital phantom of the IVD. We considered a realistic geometry of a pig's IVD, extracted from Magnetic Resonance Imaging, from which the spatially varying collagen and water proportions, respectively r_c and r_w, could be extracted. These values enabled the assignment of optical properties (absorption $\mu_a(\lambda)$ and scattering $\mu_s(\lambda)$ coefficients, anisotropy factor $g(\lambda)$) and the Grüneisen parameter Γ to each voxel of the phantom. We then generated synthetic initial pressure distributions measurements $p_o = \Gamma\Phi(\mu_a, \mu_s, g)$ under a restricted configuration (epi-detection) similar to our experimental setup. Then, we explored various approaches to reconstruct the three unknown spatially varying quantities r_c, r_w and Γ in the whole volume of the disc. A model-based regularized gradient-descent approach was adopted: the gradients were derived with the adjoint method, forward and adjoint problems were solved by Monte Carlo simulations. Two approaches were considered: (i) the law linking $\Gamma(r_c, r_w)$ and the chromophore concentrations was known *a priori*; (ii) no prior knowledge was introduced. In the latter case, ratios of measurements performed at different wavelengths (typically $\lambda_1 = 532$ nm and $\lambda_2 = 960$ nm) were considered, and Γ could be obtained from the reconstructed chromophore concentrations.

The results show that the ratio-based cost function in the model-based optical inversion scheme significantly improves the quality of the reconstructions, although regularization is essential to ensure stability.

[1]A. Capart, R. Allais, J. Wojak, O. Boiron, A. Da Silva. Quantitative Photo-Acoustic Imaging based on data normalisation: application to the reconstruction of the opto-mechanical properties of the intervertebral disc.Biomedical Physics and Engineering Express, 2025, 11 (6)