applied optics

Optical versus radiographic imaging and tomography: introduction to the ROADS feature issue

Zhehui Wang,[1,*] Wei Liu,[2] Sophia Malko,[3] and Anton Tremsin[4]

[1]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[2]Mayo Clinic, Phoenix, Arizona 85054, USA
[3]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08540, USA
[4]University of California at Berkeley, Berkeley, California 94720, USA
*zwang@lanl.gov

Received 2 April 2024; posted 2 April 2024; published 18 April 2024

Optical imaging is an ancient branch of imaging dating back to thousands of years. Radiographic imaging and tomography (RadIT), including the first use of X-rays by Wilhelm Röntgen, and then, γ-rays, energetic charged particles, neutrons, *etc.* are about 130 years young. The synergies between optical and radiographic imaging can be cast in the framework of these building blocks: *Physics, Sources, Detectors, Methods*, and *Data Science*, as described in Appl. Opt.61, RDS1 (2022). Optical imaging has expanded to include three-dimensional (3D) tomography (including holography), due in to part the invention of optical (including infrared) lasers. RadIT are intrinsically 3D because of the penetrating power of ionizing radiation. Both optical imaging and tomography (OIT) and RadIT are evolving into even higher dimensional regimes, such as time-resolved tomography (4D) and temporarily and spectroscopically resolved tomography ($4D^+$). Further advances in OIT and RadIT will continue to be driven by desires for higher information yield, higher resolutions, and higher probability models with reduced uncertainties. Synergies in quantum physics, laser-driven sources, low-cost detectors, data-driven methods, automated processing of data, and artificially intelligent data acquisition protocols will be beneficial to both branches of imaging in many applications. These topics, along with an overview of the Radiography, Applied Optics, and Data Science virtual feature issue, are discussed here.

https://doi.org/10.1364/AO.525556

1. INTRODUCTION

Pinhole imaging is one of the earliest known imaging modalities, which may predate the invention of optical lenses, such as the Nimrud lens, unearthed in 1850 [1]. Optical pinhole imaging using sunlight was recorded as early as in the fifth century BC, by the Chinese philosopher Mozi [2]. X-ray radiography, invented by Wilhelm Röntgen in 1895, is the oldest form of radiographic imaging and tomography (RadIT). The first X-ray image, similar to optical pinhole imaging, did not use an X-ray lens to modulate the wave front. RadIT have since expanded to include other sources of ionizing radiation such as energetic charged particles (electrons, positrons, protons, etc.), higher energy X-rays or γ-rays, neutrons, and muons.

Unlike optical imaging, there is no "obvious" natural sources of bright illumination such as the Sun for RadIT on Earth. X-rays, relativistic electrons, positrons and other ionizing particles from the Sun and outer space are mostly attenuated by the Earth's ionosphere and atmosphere. Natural sources of ionizing radiation, such as minerals in the ground, soil, and water, atmospheric radon (^{222}Rn) and thoron (^{220}Rn), cosmic-rays, and cosmic-ray muons do exist; however, these natural sources of ionizing radiation, which can not be detected by eyes or other human senses, may also be too weak or diffused for imaging and tomography (IT). Radon and cosmic-ray muon IT do provide useful information for environmental protection, geology, natural (e.g., earthquakes) or man-made disasters (e.g., nuclear reactor accidents) assessment through synthesized data from distributed sampling instruments [3] or a long integration time that can last for days [4,5].

In addition, optical photons and ionizing radiation have different matter-interaction physics. Optical photons can not penetrate deep into opaque objects without strong scattering, reflection, or absorption, limiting OIT to collect data mostly near the surfaces of many objects. Meanwhile, the penetrating power of ionizing radiations allow RadIT to collect data both from the surfaces and inside, and thus 3D spatial or tomography information from the scenes and objects. The differences in physics also require different models for OIT and RadIT data interpretation.

Despite their differences, the common goals of optical imaging and tomography (OIT) and RadIT are to acquire more data and information from the scenes. More data include higher temporal and spatial resolution. Modern OIT and RadIT share digital imaging technology such as complementary metal-oxide-semiconductor (CMOS) sensors and other detectors to collector data at a rate exceeding 1 TB/s [6]. More data can be extracted by using powerful IT models, iterative data algorithms, and computing hardware such as GPUs. Both computational OIT and computational RadIT, including the use of machine learning algorithms, are thriving [7]. The quests for more information and details nondestructively have led to high-dimensional imaging modalities such as time-resolved 3D (*aka* "4D") and even 4D+ methods. 4D+ RadIT require the capture of extra information about X-rays such as energy, momentum, or polarization, in addition to their position and the time of arrival which are more established. The invention of the lasers in 1960, adaptive optics, wavefront shaping, fiber optics techniques now allow optical 3D tomography [8]. The complementarity of the optical and ionizing radiation in sources and physics drive the synergies between OIT and RadIT, including multi-modal IT that use OIT and RadIT simultaneously to collect data and gather maximum amount of information. Synergies between OIT and RadIT are also driven by practical considerations such as cost reduction and compactness of the IT hardware in deployment, such as medicine, additive manufacturing, and non-destructive testing.

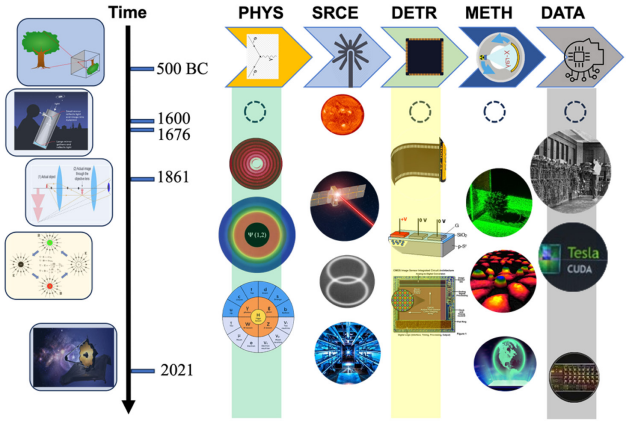

Fig. 1. We highlight some milestones in OIT in the left most column and additional examples on the right in terms of Physics (PHYS), X-ray sources (SRCE), Detectors (DETR), Methods (METH) and Data science (DATA) [9]. Time column (from the top down): Pinhole imaging using sunlight (1000 - 500 BC) [2]; Telescope (1600s) and microscope (1676) technologies advanced significantly in the 1600s; Maxwell's equations (1861); James Webb Space Telescope (2021). [PHYS] Physical optics; Quantum optics; and the Standard Model of particle physics (1970s). [SRCE] the Sun; a laser on a communication satellite; an entangled photon source; NIF lasers. [DETR] Photographic film; charge-coupled device (CCD); complementary metal-oxidesemiconductor or CMOS imaging sensors with active pixels. [METH] Hologram; Phase-contrast microscopy; Real-time hologram. [DATA] ENIAC computer; GPU accelerations and NVIDIA CUDA platform (2000s) for deep neural networks (DNNs) in 2010s; NVIDIA aerial hardware AI-on-5G on a chip for edge applications (~ 2024). Additional references to the thumbnails are listed in [10–31].

Figure 1 highlights additional synergies between OIT and RadIT in terms of physics (PHYS), illumination sources (SRCE), detectors (DETR), methods (METH) and data science (DATA). In the beginning (ancient times), there was only light from the Sun and primitive pinhole imaging. Both microscopes and telescopes made significant progress in 1600s. In 1841, the great mathematician Carl Friedrich Gauss published his classical treatise on Dioptrische Untersuchungen (Dioptric Investigations) [32], which is usually regarded as a milestone in geometrical optics. Maxwell published his famous equations starting in 1861, which unified optics with electromagnetism. Abbe's theory of vision in a microscope was first published in 1873, providing valuable theoretical insight for super-resolution microscopy. One of the latest achievements in OIT is the commissioning of the James Webb Space Telescope (JWST) in 2021. JWST combines a large optical aperture of 6.5 m, cooled low-noise detectors, background reduction designs and data processing methods that reduce the ambient noise. Nancy Grace Roman Space Telescope is expected to come online in 2027 with the largest field-of-view ever in space-based optical imaging setting.

Synergies in physics between OIT and RadIT are now described by the Standard Model of particle physics, which unifies the physics of optical photons with the physics of ionizing radiation. The Standard Model provides the framework to interpret photon-matter interactions, and ionizing radiation-matter interactions. Furthermore, the details of the interactions are now mostly understood for IT applications. OIT and RadIT may complement each other in harvesting quantum information for IT applications.

Synergies in sources. Steady increase in optical (including infrared here) laser power now also allows a new kind of synergy, e.g., to produce short pulses of X-rays, relativistic electrons, neutrons [33] and positrons by using high-power lasers [34], with emerging RadIT applications such as in nuclear fusion [35,36]. Laser-driven positrons may lead to time-resolved positron emission tomography (PET) in the near future.

Synergies in methods. We mention compressed sensing, algorithms for 3D reconstruction using sparse data, lensless imaging enabled by time-of-flight and particle/photon tracking techniques, all of which are applicable to both OIT and RadIT. Metamaterials (or subwavelength structures) for optical light guiding and wave front engineering, which can lead to super-resolution in OIT through, for example, meta-lenses through negative refractive index [37], are also finding applications for scintillators, an important material for RadIT. More information and references may be found, for example, in [36,38].

Synergies in data. Machine learning and especially deep learning are growingly used in OIT and RadIT for image processing and reconstruction. Experimental data may not always be sufficient for neutral network training. Data augmentation and data fusion methods are necessary. Machine learning also offers many different option for data fusion [39], including OIT and RadIT data fusion.

Synergies in applications. We mention radiation therapy as one area with significant synergies between OIT and RadIT. The keynote and invited talks showcased significant contributions

towards understanding and enhancing optical imaging applications in radiation therapy, from fundamental advancements in imaging technologies to the integration of artificial intelligence (AI) for improved diagnostic and therapeutic outcomes. Section 3 below gives additional details.

2. ARTICLES IN THE VIRTUAL FEATURE ISSUE

Thirteen articles have been published so far in the virtual feature issue of Radiography, Applied Optics, and Data Science (ROADS) [40], and a few more are in the final review stage. Ten of the articles belong to OIT, and two articles (Miyadera *et al.*, Pearcy *et al.*) belong to RadIT. One additional article (Kumar *et al*.) covered application in THz frequency of electromagnetic spectrum.

Most of the papers, imaging or other signal modality optimization, are motivated by a particular application, ranging from materials applications, 3D imaging applications, to biology, to hydrogen sensing, to nuclear reactor hazard mitigation, to surface cleaning, and to hypersonic phenomena. More specifically, in no particular order, Qian and Duan described an automated shrimp counting platform based on optics and image processing is designed to complete the task of counting shrimp larvae. Image signals were further optimized through illumination. An ensemble learning based method to solve the problem of low signal-to-noise ratio (SNR) Fabry–Perot sensor spectrum signal demodulation was described by Yang *et al.* In Cai *et al*.'s paper, Laser-induced breakdown spectroscopy (LIBS) combined with SG-SPXY spectral data pre-processing and back-propagation neural network predict the content of oxides in cement raw materials for real-time cement raw meal composition analysis. Zhou *et al.* described a laser-cleaning method and reported optimal laser power density through experiments. Chen *et al.* reported numerical simulation of a hypersonic boundary layer flow and focusing schlieren image synthesis, paving the way towards simulation-guided experimental design and physical interpretations of schlieren images. Miyadera *et al.* reports a muon scanner design to sort the nuclear fuel debris. One of the challenges is to operate the muon scanner in the presence of high γ-ray radiations from the debris: muon-event-identification electronics and a muon-tracking algorithm in the presence of high γ-ray radiations were developed. Li theoretically studies the axial radiation force (AOF) exerted on a uniaxial anisotropic sphere illuminated by an on-axis high-order Bessel (vortex) beams (HOBVBs). The study may be applied to micromanipulation of biological and anisotropic complex particles by optical tractor (vortex) beams. Chu *et al.* described a home-made transmission optical fiber hydrogen sensing system. Sensitivity, response time, repeatability of doped tungsten oxide films for hydrogen sensing are characterized experimentally towards film optimization. Qi *et al.* described model, simulations and experimental methods to calibrate a Pulsed light detecting and ranging (Lidar) for better 3D imaging and target identification. Pearcy *et al.* used mono-energetic proton radiography to probe laser-driven vacuum Hohlraums in OMEGA laser facility. A new technique to detangle the contributions of electric and magnetic fields to proton deflections was developed to better reconstruct proton deflection field in a single proton radiograph. Chen *et al.* proposed a gap filling method based on dual acquisition (GFDA) algorithm to fill the inter-module gap based on dual acquisition for large-area stitched X-ray detectors. The proposed algorithm is compared with B-spline interpolation and discrete cosine transform (DCT) domain iterative filling methods and has better performance in the case studies. By implementing secondary imaging and focal distance allocation, Cao *et al.* described a design of an optical dynamic target simulator. Kumar and Sadhu used machine learning to aid hardware design and optimization: Performance prediction of a circularly polarized graphene-dielectric resonator-based antenna for THz frequency application using machine learning algorithms.

3. RadIT 2023 AND HIGHLIGHTS

RadIT 2023 was convened as a hybrid (in-person and online) symposium in conjunction with the OPTICA (formerly OSA) topical meeting on Digital Holography and Three-dimensional Imaging (DH and 3D), August 14–17, 2023 (Boston, Massachusetts, USA). The symposium had keynote talks, invited talks, contributed oral presentations and posters jointly with the Optica imaging congress.

In one of the two keynote talks, Dr. Brian Pogue (University of Wisconsin, Madison) discussed the capabilities of Cherenkov-excited luminescence scanned imaging (CELSI) in detecting and quantifying molecular emissions in tissue, demonstrating its potential for *in vivo* mapping of tumor oxygenation with high sensitivity and resolution. In the other keynote speech, Dr. Lei Xing (Stanford University) explored the integration of artificial intelligence in imaging, highlighting the advancements and challenges in deploying AI for deep learning-imaging techniques, treatment planning, and clinical decision-making.

Invited talks expanded on the symposium's theme by addressing recent advancements and applications of optical and AI technologies in medical imaging and therapy. Dr. Shuai Leng (Mayo Clinic Rochester) delved into the latest developments in CT imaging, including photon counting detectors and AI's role in enhancing imaging techniques. Dr. Liangzhong Xiang (University of California Irvine) presented on X-ray induced acoustic computed tomography (XACT), a promising modality for faster and lower-dose imaging compared to traditional CT. Dr. Ken Wang (University of Texas Southwestern Medical Center) discussed optical tomography-guided systems for pre-clinical radiotherapy research, focusing on enhancing *in vivo* imaging capabilities. Dr. Daniel Robertson (Mayo Clinic Arizona) introduced high-density glass scintillators for improving proton radiography, while Dr. Xiang Li (Massachusetts General Hospital and Harvard Medical School) discussed identifying causal relationships between amyloid-beta accumulation and Alzheimer's disease progression. Dr. Wei Liu (Mayo Clinic Arizona) examined the application of AI and imaging technologies in proton therapy, emphasizing their contribution to the accuracy and efficiency of cancer treatment. Dr. Lei Tian (Boston University) presented a talk on Computational Miniature Mesoscope, which augments miniature optics with algorithms for large-scale 3D fluorescence imaging. Dr. Charles Bouman (Purdue University) presented advances in reconstruction algorithms including machine learning that can enable

high fidelity reconstructions from sparse-view CT data sets. Dr. Laura Smilowitz (LANL) discussed lab-scale asynchronous radiographic system. Dr. Anton Tremsin (UC Berkeley) highlighted recent progress in energy-resolution neutron imaging around the world. Besides applications of proton radiography for nondestructive testing and dynamic imaging (Dr. Chris Morris, LANL), Drs. Sophia Malko (Princeton Plasma Physics Laboratory) and Raspberry Simpson (Lawrence Livermore National Laboratory) discussed proton radiography as a powerful tool for National Ignition Facility and MagLIF applications to harvest nuclear fusion energy. Dr. David Brady (University of Arizona) discussed snapshot tomography on array cameras. Dr. Roarke Horstmeyer (Duke University) described multi-aperture Methods for 3D tomographic optical imaging, and computational 3D video microscopy with micro-camera arrays. Latest advances in muon tomography were highlighted by Drs. Haruo Miyadera (Toshiba Corp.) and Konstantin Borozdin (Decision Sciences International Corp.). Dr. Richard Sandberg (Brigham Young University) gave an overview on challenges and opportunities for mesoscale ultrafast imaging at X-ray free electron laser facilities (XFELs).

Funding. U.S. Department of Energy (89233218CNA000001).

Acknowledgment. The RadIT 2023 symposium was organized by Mark A. Foster (Johns Hopkins University, USA), LanGao (Princeton Plasma Physics Laboratory, USA), Matthew Hill (Lawrence Livermore National Laboratory, USA), Wei Liu (Mayo Clinic Arizona, USA), Sophia Malko (Princeton Plasma Physics Laboratory, USA), Haruo Miyadera (Toshiba, Japan), Richard Sandberg (Brigham Young University, USA), Audrey C. Therrien (University of Sherbrook, Canada), Anton Tremsin (University of California, Berkeley, USA), Singanallur Venkatakrishnan (Oak Ridge National Laboratory, USA), Zhehui Wang (Los Alamos National Laboratory, USA, symposium chair), and Vladislav V. Yakovlev (Texas A&M University, USA). The ROADS feature issue of *Applied Optics* was co-edited by Sophia Malko (Princeton Plasma Physics Laboratory, USA), Anton Tremsin (University of California, Berkeley, USA), and Zhehui Wang (Los Alamos National Laboratory, USA, lead editor).

We wish to thank DH & 3D chairs Pierre-Alexandre Blanche (University of Arizona, USA), Chau-Jern Cheng (National Taiwan Normal University, Taiwan), Pietro Ferraro (Consiglio Nazionale delle Ricerche, Italy), and Yaping Zhang (Kunming University of Science and Technology, China) for help and many suggestions with RadIT 2023 organization. We also wish to thank Optica (formerly OSA) Society and especially Kathleen Spurney (Director of events, Senior meeting manager, OPTICA), Michael Duncan (Senior Science Advisor, OPTICA), Milen Yishak (Technical Program Specialist, OPTICA), and Alex Zubelewicz (LANL) for the RadIT 2023 program, hybrid conference logistics, other suggestions and help. The *Applied Optics* feature issue would not be possible without the help and guidances from Gisele Bennett (editor), Nicole Williams-Jones, Kelly Cohen, Carmelita Washington, Rebecca Robinson, Cristina Kapler and others. Z. W. also wishes to thank Rich Sheffield (LANL) for support and encouragement.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

REFERENCES

1. Wikipedia, "Nimrud lens," https://en.wikipedia.org/wiki/Nimrud_lens.
2. Wikipedia, "Camera obscura," https://en.wikipedia.org/wiki/Camera_obscura.
3. S. K. Sahoo, M. Katlamudi, and B. C. P., "Spatial distribution and radiological risk assessment of soil radon(222 Rn) and thoron (220 Rn) in Gandhinagar city, Gujarat, India," J. Radioanal. Nucl. Chem. **333**, 1403–1417 (2023).
4. Wikipedia, "Muon tomography," https://en.wikipedia.org/wiki/Muon_tomography.
5. H. Miyadera and C. L. Morris, "Muon scattering tomography: review," Appl. Opt. **61**, C154–C161 (2022).
6. S. Lin, S. Ning, H. Zhu, *et al.*, "Neural network methods for radiation detectors and imaging," arXiv, arXiv:2311.05726 (2023).
7. Y. Zhang, H. Fan, F. Wang, *et al.*, "Polygon-based computer-generated holography: a review of fundamentals and recent progress [invited]," Appl. Opt. **61**, B363–B374 (2022).
8. Z. Yu, H. Li, T. Zhong, *et al.*, "Wavefront shaping: a versatile tool to conquer multiple scattering in multidisciplinary fields," Innovation **3**, 100292 (2022).
9. Z. Wang, "Radiographic imaging and tomography," Appl. Opt. **61**, RDS1–RDS4 (2022).
10. Thumbnail image credit: [TIME] Pinhole imaging, https://en.wikipedia.org/wiki/Pinhole_camera_model.
11. Telescope history, http://www.historyoftelescope.com/telescope-history/telescope-timeline/.
12. Telescope, https://spaceplace.nasa.gov/telescopes/en/.
13. Microscope, https://microscopy4kids.org/microscope/.
14. Maxwell's equations, https://phys.org/news/2019-10-uncover-anomaly-electromagnetic-duality-maxwell.html.
15. James Webb Space Telescope, https://science.nasa.gov/mission/webb/.
16. [PHYS]: Physical optics, https://en.wikipedia.org/wiki/Physical_optics.
17. Quantum Optics, the book cover of M. O. Scully and M. S. Zubairy, *Quantum Optics*, 1st ed. (Cambridge University, 1997).
18. The standard model of particle physics, https://notes.thatother.dev/physics/standard-model/.
19. [SRCE]: the Sun, https://science.nasa.gov/sun/.
20. Laser, https://www.nasa.gov/directorates/somd/space-communications-navigation-program/whats-next-the-future-of-nasas-laser-communications/.
21. Entangled photons, P. Kwiat, K. Mattle, H. Weinfurter, *et al.*, "New high-intensity source of polarization-entangled photon pairs," Phys. Rev. Lett. **75**, 4337–4341 (1995).
22. NIF lasers, https://en.wikipedia.org/wiki/National_Ignition_Facility.
23. [DETR] Photographic film, https://en.wikipedia.org/wiki/Photographic_film#/media/File:Undeveloped_35_mm_film.jpg.
24. CCD, https://en.wikipedia.org/wiki/Charge-coupled_device.
25. CMOS active pixel sensor https://micro.magnet.fsu.edu/primer/digitalimaging/cmosimagesensors.html.
26. [METH], Hologram, https://holocenter.org/what-is-holography/image-recording.
27. Phase-contrast microscopy, https://en.wikipedia.org/wiki/Phase-contrast_microscopy.
28. Real-time 3D hologram, https://news.mit.edu/2021/3d-holograms-vr-0310.
29. [DATA] (ENIAC, https://en.wikipedia.org/wiki/ENIAC.
30. NVIDIA Tesla CUDA, https://arnon.dk/matching-sm-architectures-arch-and-gencode-for-various-nvidia-cards/.
31. NVIDIA aerial GPU AI-on-5G on a chip, https://developer.nvidia.com/blog.
32. C. F. Gauß, "Dioptrische Untersuchungen," 1841, https://17centurymaths.com/contents/gauss/DioptrischeUntersuchungenTr.pdf.
33. A. Yogo, Z. Lan, Y. Arikawa, *et al.*, "Laser-driven neutron generation realizing single-shot resonance spectroscopy," Phys. Rev. X **13**, 011011 (2023).
34. H. Chen, S. C. Wilks, J. D. Bonlie, *et al.*, "Making relativistic positrons using ultraintense short pulse lasers," Phys. Plasmas **16**, 105001 (2009).
35. T. Ma, "Ignition and the path towards an inertial fusion energy future," LLNL-PRES 833900 (Lawrence Livermore National Laboratory, 2023).
36. Z. Wang, A. F. T. Leong, A. Dragone, *et al.*, "Ultrafast radiographic imaging and tracking: An overview of instruments, methods, data, and applications," Nucl. Instrum Methods Phys. Res. A **1057**, 168690 (2023).

37. D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, "Metamaterials and negative refractive index," Science **305**, 788–792 (2004).
38. Z. Wang, C. Dujardin, M. S. Freeman, *et al.*, "Needs, trends, and advances in scintillators for radiographic imaging and tomography," IEEE Trans. Nucl. Sci. **70**, 1244–1280 (2023).
39. Z. Wang, S. Lin, M. Teng-Levy, *et al.*, "Physics-informed meta-instrument for experiments (pimix) with applications to fusion energy," arXiv, arXiv:2401.08390 (2024).
40. "Radiography, Applied Optics, and Data Science (ROADS)," 2024, https://opg.optica.org/ao/virtual_issue.cfm?vid=599.