Sub-micro Computed Tomography through Photon Scattering-aware Diffusion

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1. Introduction

X-ray imaging constitutes a fundamental technology in medical tomography, radiation detection, and industrial non-destructive testing. High-efficiency luminescent and fast-decay scintillator materials play a critical role in converting invisible radiation into visible optical signals, thereby enabling high-energy radiation imaging using cost effective photodetector arrays. However, persistent challenges, including optical signal crosstalk, X-ray scattering, and resolution limitations, impede the advancement of next-generation low-dose, high-resolution computed tomography (CT) imaging.

2. Substantial section

The scintillator imaging system consists of a scintillator, which serves as the photon energy conversion material, and a CMOS imaging array. As shown in Fig. 1, due to the thickness of the scintillator, significant scattering occurs as the radiation propagates through the material. [1,2].

2.1 Related work

To overcome this problem, structured scintillators, such as columnar CsI: Tl arrays, have been developed to mitigate scattering effects, but their fabrication complexity and cost hinder widespread adoption [3]. Recent advancements in nanophotonic-based scintillators and computational methods, including point spread function deconvolution and deep learning-based denoising, have improved imaging quality. However, these approaches remain constrained by physical model accuracy and data generalizability [4,5].

In contrast, this study introduces a novel AI-driven conditionally constrained diffusion-based image reconstruction method, leveraging light field imaging to capture real scattering processes. By integrating physically constrained learning and image reconstruction, this approach significantly enhances resolution while reducing radiation dose, surpassing the performance of traditional scattering mitigation techniques.

2.2 Results

To evaluate the effectiveness of the proposed diffusion-based reconstruction method, experiments were conducted using a custom-built light field imaging system. 5000 sets of photon trajectory images were collected, capturing the propagation of X-ray photons through the scintillator. Specifically, the dataset was obtained by performing depth-resolved optical sectioning of the visible light generated within a transparent scintillator upon X-ray energy conversion. These physical process images serve as continuous condition constraints for diffusion model training and guide the direction of the training process through the encoder. For the reconstruction results, the evaluation focused on key performance metrics, including spatial resolution, contrast enhancement, and radiation dose reduction.

As shown in Fig. 2, the proposed method achieves a spatial resolution improvement by a factor of two, surpassing conventional X-ray imaging methods. Furthermore, image contrast is significantly enhanced, leading to clearer structural details. The method also performs well under low dose imaging conditions, demonstrating similar improvements in resolution and contrast while maintaining high-quality image reconstruction at significantly lower exposure levels.

2.3 Figures and tables

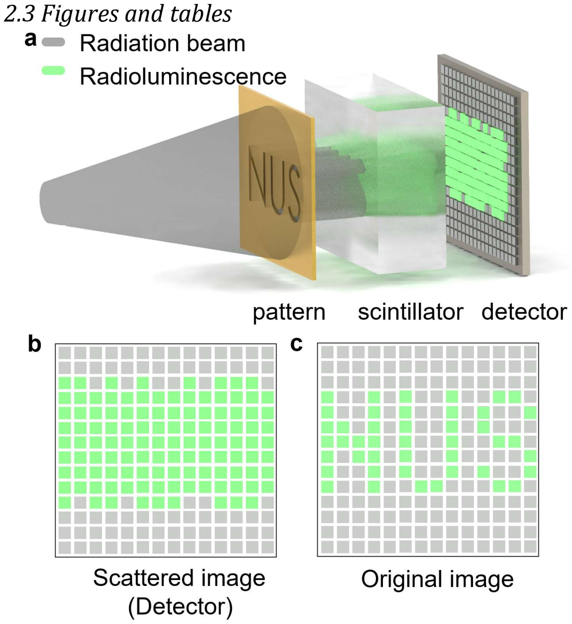

Fig. 1: Schematic of X-ray imaging. (a) A general radiation imaging system. (b, c) Comparison of scattered and original images.

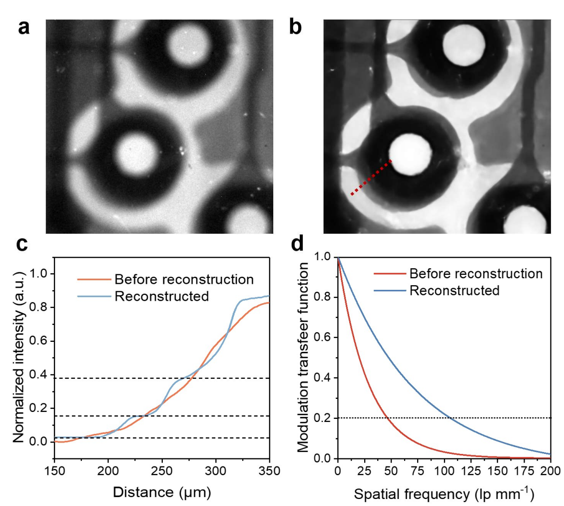

Fig. 2: Reconstruction of X-ray images of circuit board chips. (a) Raw detector image. (b) Reconstructed image. (c) Contrast comparison. (d) Resolution comparison.

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References

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Appendix A. Dataset acquisition platform

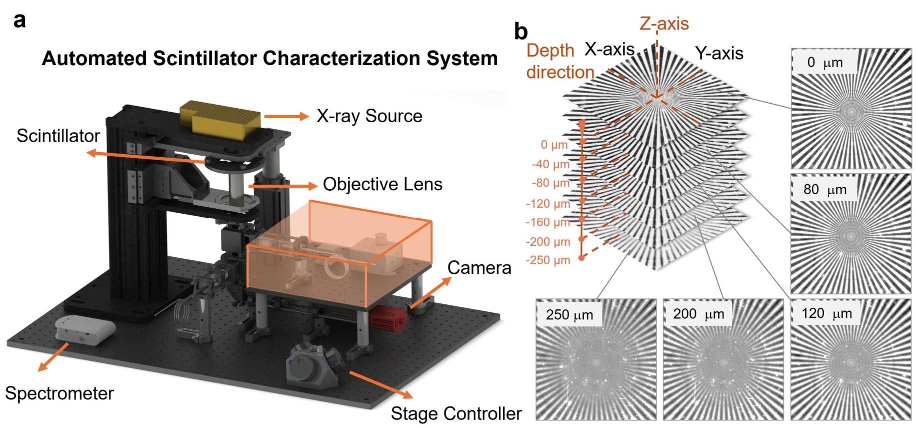

Fig. A.1 X-ray Imaging Data Acquisition System. (a) In-situ depth-scanning data acquisition setup. (b) Z-stack microscopic imaging of the scintillator under X-ray excitation.

Appendix B. Frame of diffusion model

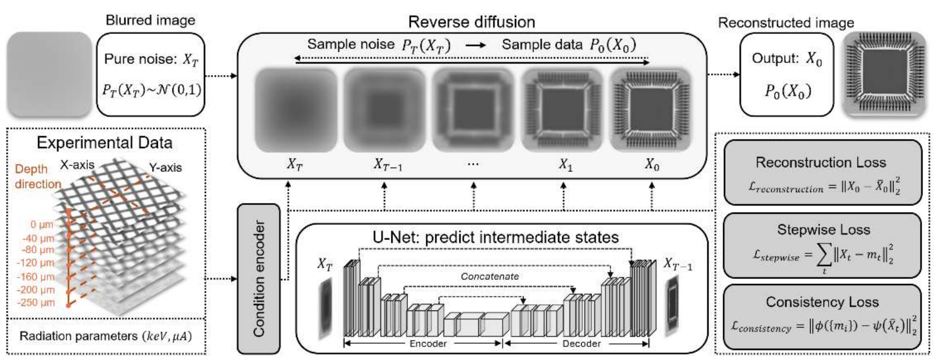

Fig. B.1 Scattering-aware diffusion model for image reconstruction. Using a continuous conditional diffusion model constrained by actual diffusion images from our own data collection platform and has high image restoration fidelity.