Contribution ID: **45** Type: 海报展示

基于蒙特卡罗的背散射多次散射校正算法

摘要

在康普顿背散射成像过程中，探测器捕获的光子不仅包括一次散射光子，还包含大量多次散射光子。如何区分和提取一次散射信号，有效降低多次散射信号对重建的不利影响，是提高重建图像的信噪比和缺陷识别能力的重要因素。本文提出了基于蒙特卡罗的康普顿背散射多次散射校正重建算法，通过两次蒙特卡罗模拟判断缺陷位置并补偿缺陷导致的散射信号变化。该方法根据实际无损检测应用场景的特点，将材料属性作为先验知识，获取材料的线性衰减系数。算法首先假设物体内部没有缺陷，得到初次粗略校正的一次散射数据。然后，使用图像分割技术区分材料与空气缺陷，并利用两次蒙特卡罗模拟精确估计原始数据中的一次散射数。通过建立连续能谱 X 射线管和康普顿背散射成像系统的数学模型，对系统矩阵进行精确建模，并使用 MLEM 算法得到信噪比更高的重建图像。为了降低蒙特卡罗模拟的噪声以改善重建效果，还提出了一种基于统计的降噪算法来减少多次散射数据中的噪声。对不同材料组成的物体以及不同尺寸缺陷的模拟结果和真实验结果显示，所提出方法可以有效提高图像的 CNR 和 SSIM，并提供更准确的物体电子密度信息，以实现更加准确的缺陷图像分割。与直接从原始数据重建相比，该方法有效改善了重建图像的信噪比。该成果在大型物体的无损检测中具有一定的实用价值。

关键词

康普顿背散射成; 蒙特卡罗; 多次散射校正

Abstract

During the process of Compton backscattering imaging, detectors capture not only single-scattered photons but also a large number of multiple-scattered photons. Distinguishing and extracting the single-scatter signals while effectively reducing the adverse impact of multiple-scatter signals on reconstruction is crucial for improving the signal-to-noise ratio (SNR) and defect identification capability of reconstructed images. This paper proposes a Monte Carlo-based correction and reconstruction algorithm for multiple scattering in Compton backscattering, which judges the defect locations and compensates for the changes in scatter signals caused by defects through two rounds of Monte Carlo simulations. The method incorporates material properties as prior knowledge to obtain the linear attenuation coefficient of the materials according to the characteristics of practical non-destructive testing applications. Initially, the algorithm assumes there are no defects inside the object to get a rough initial correction of single-scatter data. Then, image segmentation techniques are used to differentiate between material and air defects, and two rounds of Monte Carlo simulations are employed to precisely estimate the single-scatter counts in the original data. By establishing mathematical models of both continuous spectrum X-ray tubes and Compton backscatter imaging systems, the system matrix is accurately modeled, and higher SNR reconstructed images are obtained using the MLEM algorithm. To reduce noise from Monte Carlo simulations and improve reconstruction quality, a statistics-based denoising algorithm is proposed to decrease noise in multiple-scatter data. Simulation results on objects composed of different materials and with various defect sizes, as well as real experiments, show that the proposed method can effectively enhance the contrast-to-noise ratio (CNR) and structural similarity index measure (SSIM) of images, providing more accurate information about the electronic density of objects for achieving more precise defect image segmentation. Compared to direct reconstruction from raw data, this method significantly improves the SNR of reconstructed images. The findings hold practical value for non-destructive testing of large objects.

Keywords

Compton backscatter imaging; Monte Carlo; Multiple scattering correction

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Session Classification: 海报展示

Track Classification: 02 海报展示: 海报展示