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Monte Carlo Simulation of an Active Coded-aperture Based on Gamma-ray Imaging System for Omnidirectional Detection

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1. Introduction

Radiation visualization technology is advancing both domestically and internationally. This technology enables the visual detection of radiation in the event of a radiation accident, minimizing worker exposure and facilitating precise operations by identifying the location of radionuclides. Additionally, from the perspective of nuclear material monitoring, there is a growing demand for the development of radiation imaging technology to verify the movement of unreported nuclear materials. Currently developed technologies detect radioactive materials using various methods. The Compton imaging technique detects radioactive materials by utilizing the scattering angle of Compton scattering. While it has the advantage of an omnidirectional field of view (FOV), its angular resolution is limited to approximately 20 to 30°, resulting in low spatial resolution for separating radiation sources. The coded aperture method detects the location of radioactive materials by employing a collimator with a specialized pattern, utilizing physical shielding. With an angular resolution of 2.5 to 6°, it allows for easier separation of radiation sources. However, its field of view is limited, and the use of a collimator increases the system's weight.

In this study, we investigated a coded aperture-based imaging technique for omnidirectional measurement. A cylindrical geometric structure was equipped with scintillator pixels. The coded aperture pattern was designed to be formed by the scintillator itself. The system matrix was constructed, and the localization of gamma-ray sources was verified using MCNPX-PoliMi simulations. Furthermore, the angular resolution and the quality of the reconstructed images were evaluated

2. Materials and Methods

This study used a coded aperture-based imaging technique. Generally, using URA or MURA patterns allows for maximizing the peak signal-to-noise ratio (PSNR) of the reconstructed image. However, in an omnidirectional configuration, geometric noise and artifacts may affect the image. To mitigate this, a pseudo-random array pattern was used. The pseudo-random array pattern used in this study is shown in Fig. 1.

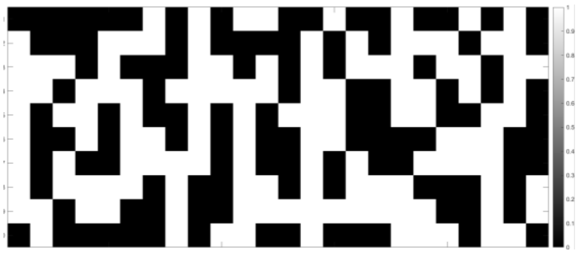

Fig. 1. Pseudo-random array pattern with a random distribution.

2.1 Geometric Structure of the Imaging System Using MCNPX-PoliMi Simulation

In this study, GAGG(Ce) was selected as the scintillation detector for system simulation, as it offers a higher light yield than NaI(Tl) while being more cost-effective than CZT or $LaBr_3$. The pattern was arranged on the surface of the cylindrical detector, and the scintillator was placed in the active regions of the pattern, ensuring that the scintillator itself formed the pattern.

A total of 128 scintillators were used, each with dimensions of 6×6× 6 mm^3, arranged in a 10×24 array. The detector model created using SolidWorks and the geometric structure implemented in MCNPX are shown in Fig. 2.

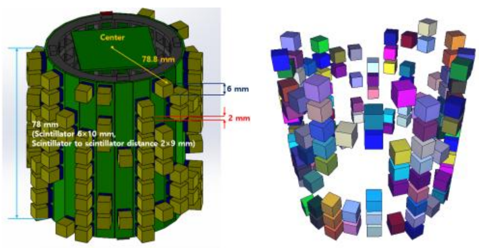

Fig. 2. Design of the active coded-aperture imaging system (left) and the geometric structure modeled using MCNPX (right).

2.2 System Matrix Construction Using MCNPX-PoliMi Simulation

To establish the omnidirectional detection system, a ^{137}Cs point source was positioned on a cylindrical surface at a distance of 1 m from the center of the geometric structure modeled in MCNPX and at a height of 2 m. For 360° detection, the system matrix of the cylindrical structure was spatially divided into a 33×105 array. A ^{137}Cs source was placed at the center of each subdivided region, and a vector was established toward the center of the scintillator. The scintillator response data for each coordinate was collected to construct the system matrix. The coordinates of the ^{137}Cs sources arranged on the cylinder and the computed system matrix are shown in Fig. 3. The system matrix calculations were performed using the numerical analysis software MATLAB.

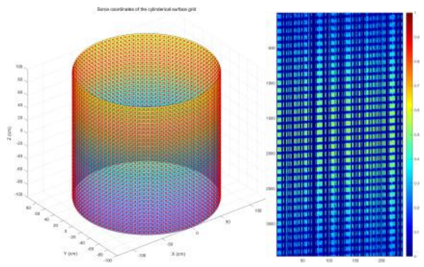

Fig. 3. ^{137}Cs source placement in the cylindrical 33×105 array (left) and the computed system matrix (right).

2.3 Image Reconstruction Test Using MLEM

To evaluate the feasibility of omnidirectional image reconstruction for the system, multiple ^{137}Cs sources were distributed at a distance of 1 m from the cylindrical geometric structure designed in Section 2.1, and images were acquired. Image reconstruction was performed using the maximum likelihood expectation maximization (MLEM) method. To enhance image quality, the reconstruction process was repeated 100 times. Additionally, to evaluate the system's performance, an angular resolution test was conducted, as shown in Fig. 4. Fig. 4(a) presents a schematic diagram for calculating the angle (θ_1) at which two sources are imaged along the longitudinal direction from the system's center. Fig. 4(b) shows a schematic diagram for calculating the angle (θ_2) at which two sources are imaged along the transverse direction. Additionally, to evaluate the image quality, the peak signal-to-noise ratio (PSNR) and structural similarity index measure (SSIM) were calculated for a single source.

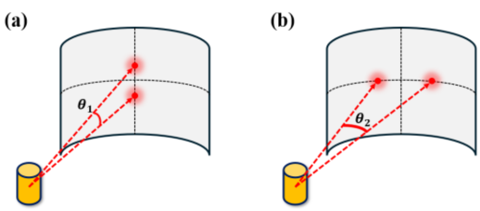

Fig. 4. Schematic diagram for angular resolution measurement. (a) Arrangement for longitudinal angle calculation and (b) arrangement for transverse angle calculation.

2.4 Image Reconstruction for Various Geometries Using MCNPX-PoliMi Simulation

The ^{137}Cs sources were arranged in various geometric configurations at a distance of 1 m from the cylindrical geometric structure designed in Section 2.1. To enhance reconstruction quality, the imaging process was repeated 100 times. To verify the image reconstruction of structures, geometric configurations were designed in the shapes of a triangle, square, ring, and character array.

3. Results

3.1 Image Reconstruction Test Using MLEM

^{137}Cs sources were placed in four directions at a distance of 1 m from the center of the cylindrical system. The acquired 2D image is shown in Fig. 5, and the 3D representation of the image is shown in Fig. 6. It was confirmed that the distribution of point sources matches the predefined coordinates. Additionally, an image evaluation was conducted for a single source. The evaluated image for a single source is shown in Figure 7, with a PSNR of 30 dB and an SSIM of 0.9.

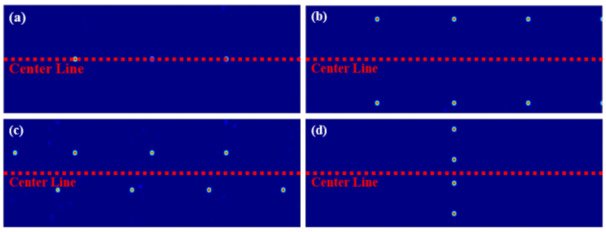

Fig. 5. 2D images of omnidirectionally placed ^{137}Cs sources. (a) Four-directional placement from the center, (b) four-directional transverse placement relative to the central axis, (c) zigzag placement relative to the central axis, (d) longitudinal placement relative to the central axis.

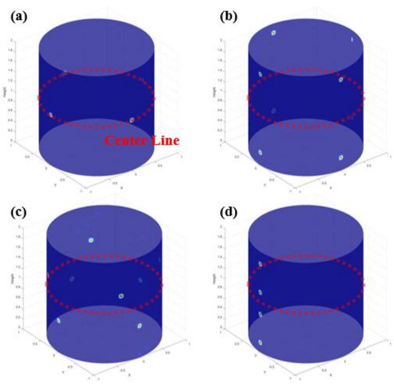

Fig. 6. 3D images of omnidirectionally placed ^{137}Cs sources. (a) Four-directional placement from the center, (b) four-directional transverse placement relative to the central axis, (c) zigzag placement relative to the central axis, (d) longitudinal placement relative to the central axis.

Fig. 7. Reconstructed image of a single source for image quality assessment.

3.2 Image Reconstruction of Various Geometric Structures Using MCNPX-PoliMi Siumlation

Various types of radiation sources exist in accident areas or for nuclear material detection. To verify various forms of image reconstruction, ^{137}Cs was defined in various geometric configurations and images were acquired. The reconstructed images obtained are shown in Fig. 7. The reconstructed images were confirmed to be similar to the established geometric configurations.

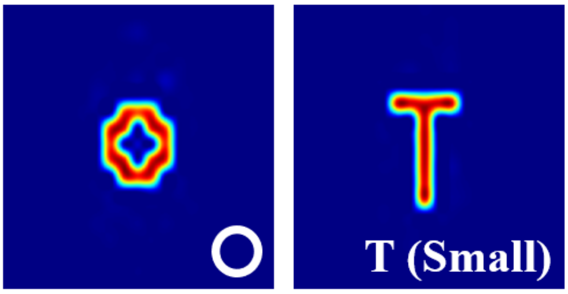

Fig. 8. Reconstructed images of ^{137}Cs defined by geometric structures. Image of ring-shaped geometric structure (left), image of character (T) shaped geometric structure (right)

3. Conclusions

In the simulation of the coded aperture-based omnidirectional imaging system, it was confirmed that images of omnidirectional sources were successfully acquired. Calculations of angular resolution yielded 6.86 degrees in the transverse direction and 5.45 degrees in the longitudinal direction. Furthermore, it was confirmed that images were successfully acquired for various forms with specific dimensions. The results obtained using MCNPX-PoliMi simulation in this study represent ideal data. While image evaluation in this study was conducted using only 137Cs, image reconstruction evaluation for the 0-3 MeV energy range will be performed in future work. Additionally, we plan to apply these simulation results to actual equipment and obtain optimal conditions through modifications such as system matrix adjustments.

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