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Implementation of a Coded Aperture Imaging System for Gamma Measurement and Experimental Feasibility Tests

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** Short Paper*

Abstract: Radioactive materials are used in medicine, non-destructive testing, and nuclear plants. Source localization is especially important during nuclear decommissioning and decontamination because the actual location of the radioactive source within nuclear waste is often unknown. The coded-aperture imaging technique started with space exploration and moved into X-ray and gamma ray imaging, which have imaging process characteristics similar to each other. In this study, we simulated 21x21 and 37x37 coded aperture collimators based on a modified uniformly redundant array (MURA) pattern to make a gamma imaging system that can localize a gamma-ray source. We designed a 21x21 coded aperture collimator that matches our gamma imaging detector and did feasibility experiments with the coded aperture imaging system. We evaluated the performance of each collimator, from 2 mm to 10 mm thicknesses (at 2 mm intervals) using root mean square error (RMSE) and sensitivity in a simulation. . In experimental results, the full width half maximum (FWHM) of the point source was 5.09° at the center and 4.82° at the location of the source was 9°. We will continue to improve the decoding algorithm and optimize the collimator for high-energy gamma rays emitted from a nuclear power plant.

Keywords: Coded aperture, Gamma ray imaging, Image & video sensing and acquisition

1. Introduction

Radioactive materials are used in medicine, non-destructive testing, and nuclear plants. If the materials are not accurately managed or are badly located, radiation can cause personal damage and health problems. Source localization is especially important during nuclear decommissioning and decontamination, because the actual location of the radioactive source within nuclear waste is often unknown [1, 2].

The coded-aperture imaging technique started with space exploration and then moved into X-ray and gamma ray imaging, which have imaging process characteristics similar to each other [3-6]. The coded-aperture approach to radiation detection is from the development of the pinhole collimator for X-ray and gamma ray imaging. A multi-pinhole collimator consists of many pinholes, and improves the signal-to-noise ratio (SNR) maintaining the diameter of the pinholes, which is an important parameter for the resolution of a pinhole imaging system [7].

In the early work on coded apertures, pinholes were randomly distributed on the collimator. The random patterns of pinholes caused difficulties with image reconstruction due to the lack of uniformity in pinhole distribution.

This problem was addressed by the development of uniformly redundant arrays (URAs) and the modified uniformly redundant array (MURA), which is based on pseudo-noise sequences and quadratic residues [8].

In this study, we designed a coded aperture collimator based on a MURA pattern to make a gamma imaging system that can localize a gamma-ray source. We simulated and modeled the coded aperture system that from a radiation source and a collimator to detector. Then

Table 1. Specifications of the simulated detector.

Features	Specifications
Material	CdZnTe
Pixel size	2 mm
Pixel pitch	2 mm
Detector module size	22 × 22 × 5 mm
No. of detector modules	2 × 2 matrix
FOV	44 × 44 mm

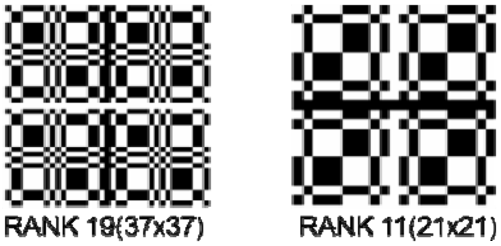
RANK 19(37x37) RANK 11(21x21)

Fig. 1. Simulated collimator pattern (MURA).

implement a direct decoding algorithm for coded aperture imaging. In addition, we designed the coded aperture collimator for our gamma imaging detector and did a feasibility test for our coded aperture imaging system.

2. Materials and Methods

2.1 Simulation

We acquired list-mode data sets of a coded aperture simulation with GATE v7.1. The detector consists of 2 × 2 modules which have an 11 × 11 CZT array. Several details are clearly summarized in Table 1.

We modeled MURA coded aperture collimators with various thicknesses. The pixel size of the collimator is determined by the detector pixel. The elements of the coded aperture are 21 x 21 (RANK 11) and 37 x 37 (RANK 19). Locations of opaque and transparent holes in the collimator array are calculated with Eq. (1) [8]:

$$A_{ij} = \begin{cases} 0 & \text{if } i = 0, \\ 1 & \text{if } j = 0, i \neq 0, \\ 1 & \text{if } C_i C_j = +1, \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

where $C_i = \begin{cases} +1 & \text{if } i \text{ is a quadratic residue modulo } p, \\ -1 & \text{otherwise} \end{cases}$

Fig. 1 shows the two kinds of MURA pattern modeled in our simulation. The RANK 19 collimator has a 2 mm pixel size and uses a 38 mm x 38 mm detector field of view (FOV), while the RANK 11 collimator has a 4 mm pixel size and uses the full FOV of the detector due to the modeled MURA coded aperture collimators with various thicknesses.

2.2 Decoding Algorithm

After getting a photon count distribution from the detector, the source direction can be determined using a decoding or reconstruction algorithm. We implemented a direct decoding algorithm to estimate location of the source, which is based on second convolution and deconvolution of the coded aperture imaging system.

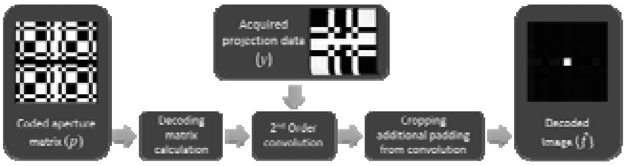

Fig. 2. Block diagram of the direct decoding algorithm in this study.

Table 2. Features of the experimental conditions.

Features	Specifications
Scintillator	**CsI, 10 mm thickness**
Detector	Hamamatsu, H8500C
Pixel size	2 mm
Pixel pitch	2.065 mm
Pixel number	21 x 21
DAQ system	Vertilon, IQSP418

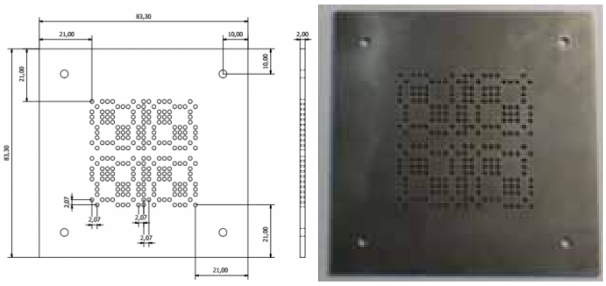

Fig. 3. Design of the coded aperture collimator (left), the tungsten product (right).

Our decoding process is shown in the following block diagram. The algorithm makes a decoding matrix for de-convolution and getting the decoding result. The final decoded image is from getting rid of the extended image matrix of the convolution result.

2.3 Experiments

We did experiments to investigate the feasibility of the coded aperture comparison imaging system and to compare the simulation results and the experimental results. We made a set of experiments with our photon detector and scintillator, which can make a high-energy gamma ray into a low-energy photon. The specifications of the detector and scintillator are listed in Table 2.

The 11 x 11 detector pixels that had superior uniformity and resolution to other areas were set as the FOV of the detector to get the experimental data. We designed a RANK 11 coded aperture collimator and made it with tungsten, which is generally used for collimators due to its high density and attenuation coefficient. Fig. 3 shows our coded aperture design and tungsten product.

We used the Co-57 gamma-ray point source, which emits 122 keV photons. The source location was 0° and 9°,

Fig. 4. Experimental imaging module (left), dark box (right).

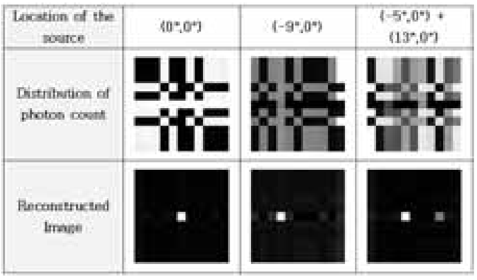

Fig. 5. Reconstruction images from RANK 11 collimator simulation.

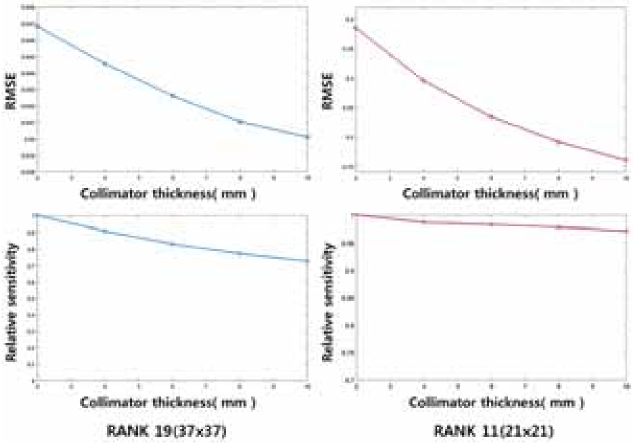

Fig. 6. RMSE and relative sensitivity depending on collimator thickness.

and we simulated the experiments with the same conditions to compare the results. The experiment was performed in a dark box to block out visible light. Fig. 4 shows our experimental imaging modules composed of the detector, the scintillator, the jig, and the collimator.

3. Results

3.1 Simulation Results

Fig. 5 shows decoding images of the simulation results with the RANK 11 coded aperture collimator. Each photon count distribution is listed in the upper line, and reconstructed images are listed in the lower line. The decoded images are 11 x 11 pixels, and pixel size is about 4.4° for a 45° FOV.

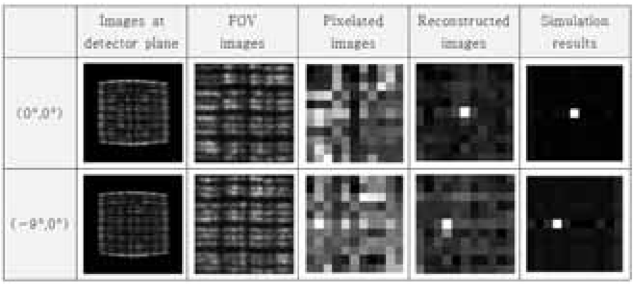

Fig. 7. Serial results of experiments.

We ran simulations with RANK 11 and RANK 19 collimators at 2 mm to 10 mm thicknesses (at 2 mm intervals) to evaluate the performance of the collimators. Fig. 6 shows the root mean square error (RMSE) of the reconstructed image and relative sensitivity to the 2 mm thick collimator.

3.2 Experimental Results

Fig. 7 shows the experimental results from the photon count distribution at the detector plane, FOV image, and 11 x 11 pixelated image, compared to the reconstructed image. The full width half maximum (FWHM) of the 0° source was 5.09°, and the 9° source was 4.82° in the reconstructed image.

4. Discussion and Conclusion

In this study, we implemented a previous coded aperture imaging system basically from simulation to experiment. In Fig. 5, our decoding process creates a source localization image that matches the actual location of sources. In experimental results, Fig. 7 shows reliable results compared to the simulation results. We will continue to improve the decoding algorithm, and will optimize the collimator for high-energy gamma rays emitted from nuclear power plants.

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