Radiation imaging system based on the 32-FCNN and monolithic crystal detector

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Date: 2025-05-09T00:00:00+00:00

Abstract

This paper proposes a radiation imaging system based on neural network ray positioning and a monolithic crystal detector. The monolithic crystal detector consists of a 5mm-thick monolithic LaBr3(Ce) crystal coupled with a SiPM array, demonstrating excellent system uniformity under 662 keV gamma-ray irradiation from Cs-137, with an energy resolution of 5.3%. By employing a 32-FCNN ray positioning model, the imaging system achieves an intrinsic spatial resolution of 2.67 mm, with an effective output area covering 81.3% of the detector surface, showing good positional linearity. The imaging capability of the system was evaluated through experiments. Results indicate that when an I-131 source is positioned 82 cm from the detector, with a focal length a of 10 cm (distance between detector and coding plate) and object distance b of 72 cm (distance between radiation source and coding plate), the reconstructed central point-source image using maximum likelihood estimation reconstruction algorithm with 20 iterations achieves a signal-to-noise ratio (SNR) of 14.2. Furthermore, the system exhibits a spatial resolution of 21 mm and an imaging range of $±$11.2°.

Full Text

Preamble

This paper proposes a radiation imaging system based on neural network ray positioning and a monolithic crystal detector. The monolithic crystal detector consists of a 5 mm-thick monolithic $LaBr_3$(Ce) crystal coupled with a SiPM array, demonstrating excellent system uniformity under 662 keV gamma-ray irradiation from Cs-137, with an energy resolution of 5.3%. By employing a 32-FCNN ray positioning model, the imaging system achieves an intrinsic spatial resolution of 2.67 mm, with an effective output area covering 81.3% of the

detector surface, showing good positional linearity. The imaging capability of the system was evaluated through experiments. Results indicate that when an I-131 source is positioned 82 cm from the detector, with a focal length *a* of 10 cm (distance between detector and coding plate) and object distance *b* of 72 cm (distance between radiation source and coding plate), the reconstructed central point-source image using maximum likelihood estimation reconstruction algorithm with 20 iterations achieves a signal-to-noise ratio (SNR) of 14.2. Furthermore, the system exhibits a spatial resolution of 21 mm and an imaging range of $±$11.2°.

Keywords: Radiation imaging system; FCNN neural network; monolithic crystal; Spatial resolution; Imaging range

Introduction

Pixelated crystal arrays are commonly used to construct position-sensitive detectors for gamma radiation imaging systems. Pixelated crystal arrays have good position linearity and spatial resolution, and their compression effects are relatively small. However, they suffer from poor energy resolution and low detection efficiency [**?**]. Compared with pixelated crystals, detectors using monolithic crystals can provide higher detection efficiency and better energy resolution [**?**], which is particularly important for spectroscopic imaging systems. However, due to the severe compression effect of monolithic crystal detectors, when using monolithic crystal detectors to form radiation imaging systems, it is necessary to study new algorithms or models for locating the interaction position of rays with the detector to reduce the impact of compression on imaging.

The positioning algorithms used for gamma radiation imaging mainly include the look-up-table (LUT) method, the maximum likelihood (ML) method, the classical center-of-gravity (COG) method, the truncated center-of-gravity (TCOG) method, and the raise-to-power (RTP) method. The LUT and ML methods can improve imaging quality but require multiple experiments to obtain the photon response function. The COG method estimates the interaction position by determining the centroid of the scintillation light, which is highly affected by the light field compression effect, resulting in poor edge resolution of the image and a reduced useful field of view (UFOV) of the detector [**?**].

Artificial intelligence algorithms have been applied to gamma-ray imaging systems. The K-nearest neighbor (KNN) algorithm has been used to calculate the photon interaction positions in positron emission computed tomography (PET) and Compton cameras, with a resolution as high as 3 mm. However, the long computation time and calibration measurements limit the application of KNN [**?**, **?**]. Feedforward neural networks (FFNNs), such as multilayer perceptrons (MLP) and radial basis function (RBF) networks, have also been used for gamma-ray positioning [**?**]. Compared with KNN, FFNNs have higher spatial resolution and can perform calculations more rapidly.

In previous studies, we developed a gamma-ray imaging system model based on a monolithic $LaBr_3$(Ce) crystal [?]. We obtained the response based on the distribution of scintillation photons and established a gamma-ray positioning model based on Convolutional Neural Networks (CNN). This positioning model can effectively improve position linearity and enhance the useful field of view (UFOV) of the imaging system. Research has shown that the neural network positioning model exhibits significant generalization ability with respect to the crystal' s energy and thickness when applied to monolithic crystal radiation imaging systems, and the signal-to-noise ratio of the images is significantly improved. In this study, based on our previous work, we developed a physical imaging system using a monolithic $LaBr_3$(Ce) crystal detector and introduced the Full Connect Neural Networks (FCNN) algorithm to achieve ray positioning. We also evaluated its imaging performance. Compared with CNN, FCNN has greater advantages in terms of computational speed and storage requirements, and it imposes lower demands on the detector readout electronics system. In physical imaging experiments, it demonstrated good energy resolution, spatial resolution, and effective field of view.

2. Radiation Imaging System

We used the Monte Carlo software Geant4 to establish an imaging detector model based on a monolithic crystal. The model consists of a 51 mm × 51 mm × 5 mm monolithic $LaBr_3$ crystal and a 16 × 16 SiPM array of the Micro-30035-TSV type. In the simulation, we digitized the detector pulse signals to enable the detector to output a response matrix. Simulation studies have shown that the CNN neural network algorithm can achieve good ray positioning and exhibits good generalization ability in terms of energy and position [?]. Based on the simulation calculations, a radiation imaging system using a monolithic $LaBr_3$(Ce) detector was developed. This radiation imaging system mainly consists of a monolithic crystal imaging detector, a coded aperture, a signal readout electronics system, an FPGA-based digital signal processing system, and a 32-FCNN ray positioning module based on Jetson Xavier NX, as shown in Figure 1 [Figure 1: see original paper].

The monolithic imaging detector is constructed with a 51 mm × 51 mm × 5 mm $LaBr_3$:Ce crystal and 256 pieces of Micro-30035-TSV SiPMs. The high density of the $LaBr_3$:Ce crystal is 5.2 g/cm^3, with a light yield of 63,000 photons/MeV and a decay time of 16 ns. The $LaBr_3$(Ce) crystal contains ^{138}La and ^{227}Ac, which exhibit intrinsic radioactivity. In the low-energy region (0–1800 keV), the intrinsic radioactivity is due to the 789 keV and 1436 keV gamma rays produced by ^{138}La. The total activity of ^{138}La in the crystal is 18.6 Bq (1.428 Bq/cm^3) [?]. Since the crystal is only 5 mm thick and has a small overall volume, the probability of 789 keV and 1436 keV gamma rays depositing energy within the crystal is low, and their impact on imaging can be neglected. In the high-energy region (1800–2800 keV), the rays that interfere with imaging mainly come from ^{227}Ac and environmental background radiation. Since their count contributions are very low compared to the object being measured, their impact on imaging quality is also minimal.

The photoelectric conversion is achieved using a 16 × 16 Micro-30035-TSV SiPM array. The sensitive area of the Micro-30035-TSV is 3.07 mm × 3.07 mm, and the package area is 3.16 mm × 3.16 mm. To achieve better energy resolution, five faces of the detector are wrapped with ESR (Enhanced Specular Reflector), and the light-emitting surface is sealed with glass. The light-emitting surface and the SiPM array are coupled using EJ-550 silicone grease. The scintillation light produced by the interaction of gamma photons with the crystal will be distributed across all 256 SiPMs, so each SiPM pixel can only detect a small number of photons. Since the light yield of $LaBr_3$:Ce is 63 photons/keV, when a 662 keV gamma photon deposits its full energy, it can produce approximately 42,000 photons. Without considering light absorption, the SiPMs will receive an average of about 165 photons. Assuming an average conversion efficiency of 30% for photon-electron conversion, each SiPM will produce an average of about 50 photon-electrons.

To reduce the complexity of the readout electronics, the signals from the 16 × 16 SiPM array are divided into 16 rows (X direction) and 16 columns (Y direction). The signals from the 16 SiPMs in each row are summed to obtain 16 row signals, X_1-X_{16}. Similarly, the signals from the 16 SiPMs in each column are summed to obtain 16 column signals, Y_1-Y_{16}. There are a total of 32 channel pulse signals in the X and Y directions. After being processed by the charge amplifier and comparator, the 32-channel pulse signals are converted into 32-channel rectangular pulse signals and sent to the FPGA for pulse width measurement.

Fig. 1. (Color online) (a) schematic diagram of the radiation imaging system, (b) radiation imaging system.

3. Gamma Ray Positioning Model Training

In our previous simulation research, we recognized that although the positioning accuracy of the CNN positioning model is slightly higher than that of the 32-FCNN model, the cost associated with using the CNN positioning model is significantly higher than that of the 32-FCNN model. On one hand, the CNN positioning model requires a larger amount of input information, necessitating full-channel readout of the SiPMs, which increases the complexity of the detector readout electronics system. On the other hand, due to the large volume of data that needs to be transmitted in the CNN neural model, higher data transmission bandwidth is required, and the demand for computational resources is also greater. To facilitate easier physical implementation, we adopted the 32-FCNN ray positioning model to achieve ray positioning.

To train the 32-FCNN ray positioning model, it is necessary to use a collimated beam to scan the detector surface to obtain the detector response signals corresponding to known incident events, thereby forming training label data. Since the resolution of the 32-FCNN ray positioning model is mainly affected by the scanning precision, the higher the scanning precision, the better the resolution. Given that the smallest coding unit of the coded aperture used in the radiation imaging system is 4 mm, and the ray positioning resolution is required to be less than 4 mm, a minimum scanning matrix of 12×12 is needed to scan the detector with a crystal side length of 51 mm. To achieve better positioning results, this st scanning matrix, with a collimator hole diameter of 2.5 mm and a scanning step size of 2.4 mm.

During the scanning of the imaging detector, a collimator with a hole diameter of 2.5 mm was used to collimate the gamma rays emitted from a liquid I-131 source with an activity of 1 mCi, forming a beam to perform stepwise scanning on 21×21 regions of the detector' s incident surface. Since the number of scanning points for the imaging detector is relatively low, the scanning time is much shorter than the half-life of the I-131 source (8 days). Therefore, the same measurement time was used for each region during the scanning process. In this study, the measurement time for each scanning region of the imaging detector was 4 minutes, with a total measurement time of 29.4 hours. Each measurement region obtained 400 sets of valid data, resulting in a total of 176,400 sets of response data for the 32-FCNN ray positioning model.

4. Performance Test of the Radiation Imaging System

The experimental tests mainly focused on the following aspects of the radiation imaging system: energy resolution, effective output area, intrinsic spatial resolution, position non-linearity, imaging signal-to-noise ratio (SNR), field of view (FOV), and spatial resolution of the imaging system.

4.1. Detector Energy Resolution Test

The energy resolution of the imaging detector was tested in this study, as shown in Fig. 2 [Figure 2: see original paper]. The detector achieved an energy resolution of 15.1% for the 365 keV gamma rays emitted by the I-131 source and 5.3% for the 662 keV gamma rays emitted by the Cs-137 source. Since the $LaBr_3$ crystal used in this study is only 5 mm thick, many gamma rays do not deposit their full energy within the crystal, resulting in relatively lower energy resolution compared to detectors that are 2 inches or 3 inches thick. In other studies, a detector composed of a 50 mm × 50 mm × 6 mm monolithic $LaBr_3$ crystal coupled with a multi-anode H8500 position-sensitive photomultiplier tube achieved an energy resolution of 6.2% at 662 keV [?]. Compared to this, the imaging detector in this study has a similar crystal size but slightly better energy resolution.

4.2. Inherent Spatial Resolution Test

We placed a tungsten steel cylinder with a diameter of 33 mm and a thickness of 15 mm at the center of the detector' s incident surface, featuring a collimation hole at the center with a diameter of 2.5 mm. The tungsten steel cylinder was shielded by tungsten steel plates around its periphery. In the experiment to test the intrinsic spatial resolution of the imaging detector, an I-131 source was positioned 750 mm above the detector. The rays passed through the tungsten steel collimation hole to irradiate the detector, while the remaining rays were attenuated by the tungsten steel shielding, as shown in Fig. 3 Figure 3: see original paper. Fig. 3(b) presents the results of the intrinsic spatial resolution test of the imaging detector. In the upper-left irradiation image, the center shows a circular bright spot, surrounded by darker areas. This is because the rays passing through the collimation hole were not absorbed by the tungsten steel, allowing the detector to record more incident events in that region, thus forming the circular bright spot. Other areas, shielded by tungsten steel, had lower detection counts, appearing as dark regions. The edge areas were brighter due to the compression effect, which led to higher counts.

Fig. 3(b) displays the projection image of the collimation hole. The higher counts from the circular collimation hole resulted in a Gaussian peak shape in the projection image. To calculate the intrinsic spatial resolution of the imaging detector, we divided the detector' s incident surface into 105 $\times$ 105 pixels. The FWHM (Full Width at Half Maximum) of the projection image of the collimation hole was 5.5 pixels. Given that the crystal side length is 51 mm, the intrinsic spatial resolution of the imaging detector was calculated to be 2.67 mm.

Fig. 3. (Color online) (a) intrinsic spatial resolution test, (b) the projection image of the collimation hole.

4.3. 32-FCNN Positioning Effect Test

Tungsten steel blocks were placed on the detector' s incident surface to test the positioning accuracy of the 32-FCNN ray positioning model, as shown in Fig. 4 [Figure 4: see original paper]. During the test, an I-131 source with an activity of 200 µCi was positioned 750 mm away from the detector. This distance is 10.5 times the detector' s side length, which meets the uniform field imaging standard in GB/T 18989-2013, where the source-to-detector distance should be no less than five times the diameter of the useful field of view (UFOV) to ensure uniform irradiation of the imaging detector. The measurement time was 25 min, and the test results are shown in Fig. 4(a) and Fig. 4(b).

In Fig. 4(a), three tungsten steel blocks were placed on the detector' s incident surface. Each block measured 12 mm $\times$ 10 mm and covered an area of 12 mm $\times$ 30 mm. Fig. 4(b) shows the imaging results of the tungsten steel blocks by the detector. The black areas have lower counts, while the white areas have higher counts. The black areas represent the rectangular shapes covered by the tungsten steel blocks. The imaging results demonstrate that the 32-FCNN ray positioning model can accurately locate the interaction positions of rays with the detector. The boundaries of the imaging region coincide with the boundaries of the 19 × 19 scanning area. Since the side length of the $LaBr_3$ crystal is 51 mm and is divided into 21 square scanning areas, each with a side length of 2.43 mm, the effective field of view of the imaging detector covers 19 areas, with a total length of approximately 46 mm, which is 81.3% of the crystal’ s incident area.

The length and width of the tungsten steel block obtained from the imaging are denoted as L and W, respectively. The actual length L of the tungsten steel block is 30 mm, while the imaged length is 29.65 mm, resulting in an error of 1.2%. The actual width W is 12 mm, while the imaged width is 11.08 mm, resulting in an error of 7.5%. The imaging results indicate that the imaged dimensions are slightly shorter than the actual dimensions. This is due to the compression effect, which causes the positioning to shift towards the center. However, the errors are small, indicating that the positioning algorithm can effectively reduce the impact of the compression effect.

Fig. 4. (Color online) (a) the placement of tungsten, (b) the projection image of tungsten.

4.4. Positional Linear Response Test

To measure the position linearity response of the imaging detector, in the uniform field radiation, a tungsten steel circular collimator with an aperture of 2.5 mm was used to scan seven positions on the K-th row of the incident surface. The positioning results of the scanned points were obtained to determine the functional relationship between the positioning points and the incident points. Fig. 5 Figure 5: see original paper shows the scanned points in the position nonlinearity experiment, namely KB, KE, KH, KK, KN, KQ, and KT. The spacing between each scanned point is 4.85 mm, which is greater than the intrinsic resolution of the imaging detector (2.67 mm). Fig. 5(b) presents the positioning image of the scanned points, showing that the imaging system captured images of the seven scanned points. The spacing between the positioning points is not uniform; for example, the spacing between points KT and KQ is significantly smaller. This is due to the compression effect, which causes each event’ s positioning result to shift towards the center, resulting in an overall inward shift of the positioning results. The slight differences in the Y direction among the seven positioning points are mainly due to the errors in moving the scanning source.

Fig. 5(c) shows the profiles of different scanned points on the K-th row. We performed Gaussian fitting on the seven peaks to obtain the pixel values corresponding to each peak, which serve as the positioning results of the measured points. Therefore, the actual measured positions and positioning positions can be calculated using the pixel values mentioned in Section 4.2, as shown in TABLE 1 .

Fig. 5(d) shows the position linearity response of the imaging detector. We performed a linear fit between the positioning coordinates and the measured coordinates, as shown in Equation 1.

$$y = 1.03x - 0.19$$

In the equation, x represents the measured position, and y represents the positioning location. The slope $k = 1.03 \pm 0.02$, the intercept b = -0.19 $\pm$ 0.67, and the coefficient of determination R^2 (COD) = 0.998. Therefore, the imaging detector and ray positioning model proposed in this paper have achieved an excellent position linearity response.

Fig. 5. (Color online) (a) scan points, (b) positioning positions for different scanned points, (c) peak position, (d) linear positional relationship.

TABLE 1. Measured positions and positioning positions for different scanned points

Scanned Point	Incident Position (mm)	Positioning Position (mm)	Error (mm)

4.5. Imaging Test

In the coded aperture imaging experiment, the distance between the imaging detector and the coded aperture plate was 82 cm, with the center of the coded aperture plate aligned horizontally with the imaging detector. The coded aperture plate used a nested-17 coding pattern. The imaging system captured the projection of the radioactive source onto the coded aperture plate within a set time frame, and the projection data were then sent to the Jetson Xavier NX for decoding. After calibrating the center, we placed a single vial of I-131 liquid source with an activity of approximately 50 µCi and a diameter of 11 mm at three different positions on the imaging platform. The focal length a was 10 cm (the distance between the detector and the coded aperture plate), and the object distance b was 72 cm (the distance between the radioactive source and the coded aperture plate). Each measurement lasted for 25 minutes, with a collected count of approximately 50k, and the maximum likelihood estimation reconstruction algorithm was iterated 50 times.

The reconstruction results of the radioactive sources are shown in Fig. 6 [Figure 6: see original paper]. Figure 6(a1) shows the positions of the radioactive sources on the imaging platform, which were 1# (-4 cm, 3 cm), 2# (9 cm, 2 cm), and 3# (-4 cm, -2 cm). As can be seen from the reconstructed images in Fig. 6(a2)-(a4), the imaging system clearly reconstructed the radioactive sources with minimal artifacts, and the signal-to-noise ratio (SNR) was around 14.2.

To quantitatively test the spatial resolution of the imaging system, we placed two vials of I-131 liquid with a diameter of 11 mm on the imaging platform and gradually increased the distance between the two liquid sources. The minimum spatial resolution of the imaging system was determined based on the imaging results. During imaging, the focal length was $a = 10$ cm, the object distance was $b = 72$ cm, and the vertical distance from the point sources to the detector' s incident surface was 82 cm. The measurement time was 40 minutes, with approximately 80k counts collected each time. Figure 6(b1) shows the positions of the radioactive sources on the imaging platform, while Fig. 6(b2)-(b4) show the reconstructed images at the corresponding positions.

When the two radioactive sources were placed at positions 1# (7.5 mm, 0 mm) and 1' # (-7.5 mm, 0 mm), the reconstructed image is shown in Fig. 6(b2). The image appears as a single hotspot, indicating that the distance between the two sources was too small for the imaging system to resolve them as separate entities. The spatial resolution of the imaging system was insufficient to distinguish the two sources with a distance $d = 15$ mm. When the two radioactive sources were placed at positions 2# (8.5 mm, 0 mm) and 2' # (-8.5 mm, 0 mm), the reconstructed image in Fig. 6(b3) appears as a linear source. This is because, although the distance between the sources increased, it was still within the minimum resolvable distance, and the reconstruction result was intermediate between a "single source" and "two sources." When the two radioactive sources were placed at positions 3# (10.5 mm, 0 mm) and 3' # (-10.5 mm, 0 mm), the reconstructed image in Fig. 6(b4) clearly shows the separation of the two sources. This indicates that the minimum distance $d = 21$ mm is the smallest distance at which the imaging system can distinguish two radioactive sources under the current imaging geometry. The spatial resolution of the imaging system is 1.47°, while the theoretical resolution is 1.37°. The discrepancy between the physical experimental resolution and the theoretical design is 7%.

To determine the imaging range of the system, we moved the radioactive source along the X-axis in the imaging platform coordinate system. During imaging, the focal length a was 10 cm, the object distance b was 72 cm, and the vertical distance from the point source to the detector' s incident surface was 82 cm. Each measurement lasted for 30 minutes, with a collected count of 6.5×10^4. The reconstructed images and the imaging range are shown in Fig. 6(c1)-(c4). In Fig. 6(c1)-(c4), when the radioactive source was moved to (-17 cm, 0 cm), the reconstructed source appeared at the far left edge of the field of view in Fig. 6(c2), indicating the left boundary of the imaging field of view. When the radioactive source was moved to (16 cm, 0 cm), the reconstructed source appeared at the far right edge of the field of view in Fig. 6(c4), indicating the right boundary of the imaging field of view. Therefore, when using the MURA-17 coded aperture for imaging with a focal length $a = 10$ cm and an object distance $b = 72$ cm, the radioactive source was moved from (-17 cm, 0 cm) to (16 cm, 0 cm), resulting in a displacement of 33 cm along the X-axis. The useful field of view angle was $±$11.2°, while the theoretical field of view angle is $±$11.3°. Thus, the physical experimental imaging range achieved 99% of the theoretical value.

Fig. 6. (Color online) (a1) − (a4) the point source reconstruction image, (b1)

− b4 the spatial resolution test, (c1) − (c4) the useful field of view angle test.

5. Summary

In this study, we have developed a radiation imaging system based on neural network ray positioning and a monolithic crystal detector. The 32-FCNN ray positioning model replaced traditional positioning algorithms, overcoming the compression effect of the monolithic crystal on the reconstruction image and achieving an effective output area of 81.3% of the detector' s active area. The intrinsic spatial resolution of the radiation imaging system reached 2.67 mm, with good position linearity. The system utilized the Jetson Xavier NX to implement 32-FCNN ray positioning with GPU parallel computing, significantly increasing the ray positioning calculation speed. The positioning calculation for 10,000 sets of ray interaction events took only 11.5 ms. When the radiation imaging system used a MURA-17 coded aperture for imaging, with a source-to-detector distance of 82 cm (focal length $a = 10$ cm, object distance $b = 72$ cm), the spatial resolution for I-131 sources reached 1.47°, which is better than that of traditional gamma-ray imaging systems. The imaging range achieved $±$11.2°, with only a 1% difference from the theoretical design value. In summary, the new imaging method proposed in this paper has significant advantages and a promising future in the development of low-cost, high-precision radiation imaging systems or instruments.

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Note: Figure translations are in progress. See original paper for figures.