Detector design for AIDER Compton Camera Using Neural Networks

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Abstract

As part of the European AIDER project, a high-performance Compton camera is being developed for radionuclide therapy using monolithic crystals (LaBr3/CeBr3) and SiPM arrays. To optimize the system, a hybrid CNN-DNN approach was implemented to precisely locate photon interactions. The key innovation is the active correction of edge effects by integrating systematic errors into the neural networks. This improves spatial resolution (FWHM) and allows for the use of larger SiPM pixels, which significantly reduces the number of required readout channels.

Introduction

Targeted Radionuclide Therapy (TRT) leverages radiopharmaceuticals to deliver selective radiation to cancerous tissues. A fundamental requirement for clinical safety and efficacy is the precise quantification of the radiation dose delivered to both lesions and organs at risk. Despite its importance, current imaging performance remains sub-optimal, particularly for alpha-emitting radionuclides. While these emitters are highly effective due to their cytotoxicity, they pose a significant challenge for conventional gamma cameras, which struggle with their high energy and low activity levels. To address this unmet need, the AIDER project [1] is developing a specialized imaging system based on Compton Camera (CC) technology. By integrating cutting-edge detectors and advanced electronics, AIDER aims to push the boundaries of current system performance. The development process includes Monte Carlo optimization and the creation of advanced reconstruction algorithms [7] to enable quantitative imaging and dosimetry. Recent advances in neural networks and signal processing are being explored to further improve these capabilities. The system's performance will be rigorously validated in clinical settings through a three-stage approach: using 3D-printed phantoms, anthropomorphic models, and finally, direct patient trials. This multi-disciplinary consortium seeks to significantly enhance image quality and sensitivity, ultimately paving the way for personalized radionuclide therapy through accurate, image-based dosimetry.

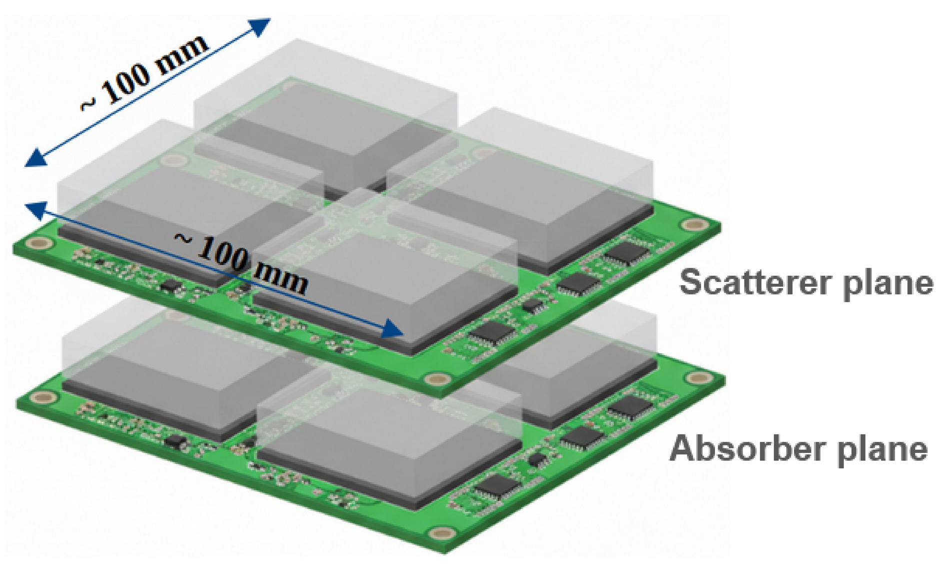

Figure 1: Schematic representation of the Compton Camera for AIDER.

Reconstruction Methodology

To determine photon interaction positions in the AIDER Compton camera, the IRIS group initially utilized the Li method [4], an analytical model that outperforms standard center-of-gravity techniques. However, this method suffers from edge effects and image compression near the crystal boundaries due to light truncation. To mitigate these biases, this work explores a hybrid Neural Network (NN) approach combining a CNN and an MLP. By leveraging the spatial feature extraction of CNNs and the corrective capabilities of deep learning [5-9], this new approach aims to eliminate systematic positioning errors and optimize spatial resolution across the entire detector volume.

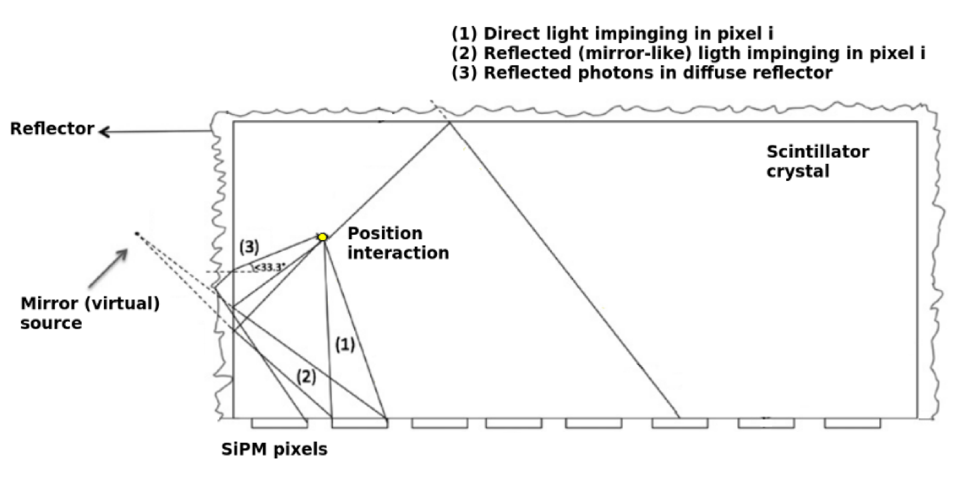

Figure 2: Li's interaction position reconstruction method in monolithic crystals.

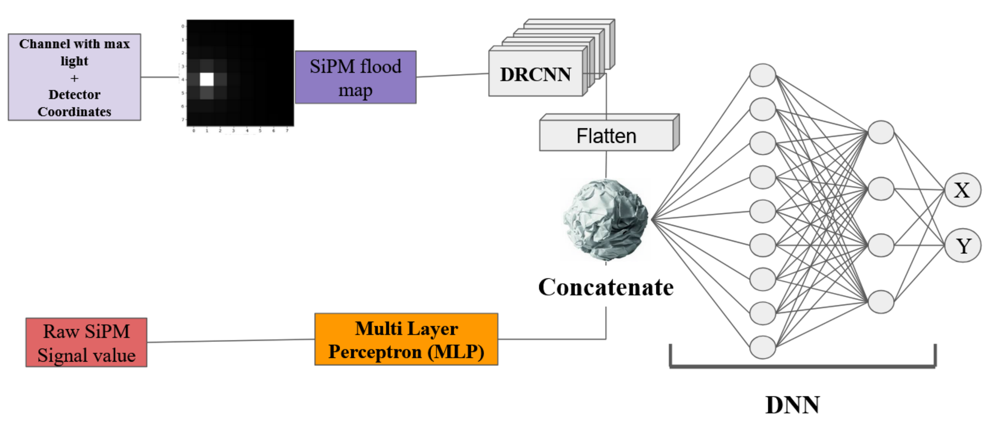

Figure 3: NN's interaction position reconstruction method in monolithic crystals.

Results

The performance of the reconstruction methods was evaluated by comparing the estimated positions against the ground-truth simulation coordinates. Metrics included Mean Absolute Error (MAE), Root Mean Square Error (RMSE), spatial error in the XY plane, and Full Width at Half Maximum (FWHM) as resolution indicators.

Quantitatively, the hybrid model consistently yielded lower FWHM values than the Li method across all configurations (Table I). Qualitatively, the Li method exhibited increasing systematic errors in the peripheral regions due to edge effects; in contrast, the proposed architecture maintained a more homogeneous error distribution.

The error data demonstrate that, based on simulation results, the values achieved for the 6 mm pixel size configuration remain close to those of the other configurations. Given the significant benefit of reducing the number of readout channels in the detector design, this will be the selected configuration if confirmed by experimental measurements with the acquired array. Finally, a direct comparison between nominal coordinates and those obtained with the Li and NN methods confirms the systematic superiority and enhanced performance of the proposed approach

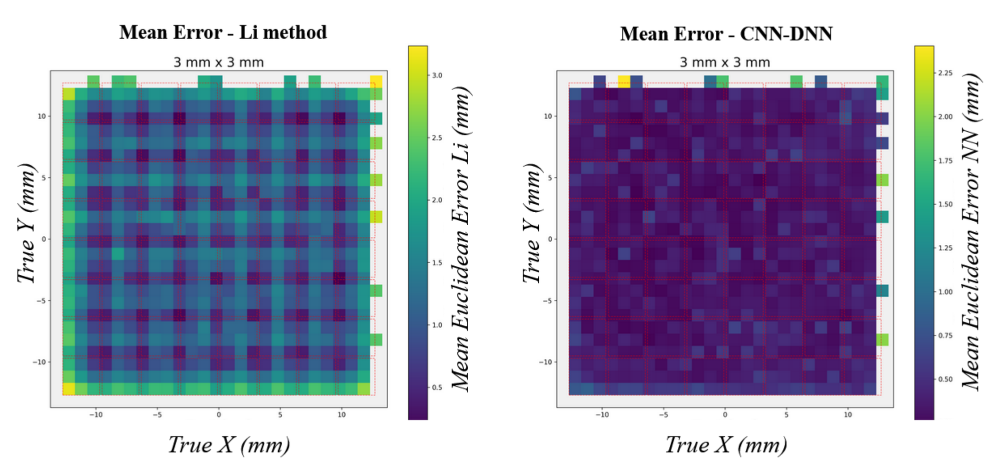

Figure 4: Comparison between estimated positions for the NN and Li methods across the entire detector.

Quantitative Comparison

Table 1: Comparison of detector configurations and performance (FWHM in mm).

Developer	Pixels x side	Pixel size	Gap size	FWHM Li	FWHM NN
Hamamatsu	8	3 mm	0.2 mm	1.80	**0.63**
Hamamatsu	8 (4 arrays)	4 mm	0.2 mm	2.02	**0.64**
OnSEMI	8	6 mm	0.2 mm	2.25	**0.70**

Experimental Outlook and Future Developments

The transition from simulation to empirical validation is currently underway. Both the OnSEMI and Hamamatsu SiPM arrays have already been acquired and are ready for testing. Experimental measurements will commence with the OnSEMI crystal configuration to validate the superior performance and edge-effect correction observed in our neural network models.

While the Compton Camera (CC) is still under active development, our immediate roadmap focuses on a critical milestone: the estimation of the Z-component (Depth of Interaction). Achieving high resolution in the Z-coordinate is of paramount importance for our system, as it will enable full 3D reconstruction and significantly enhance the overall imaging sensitivity and accuracy for TRT applications.

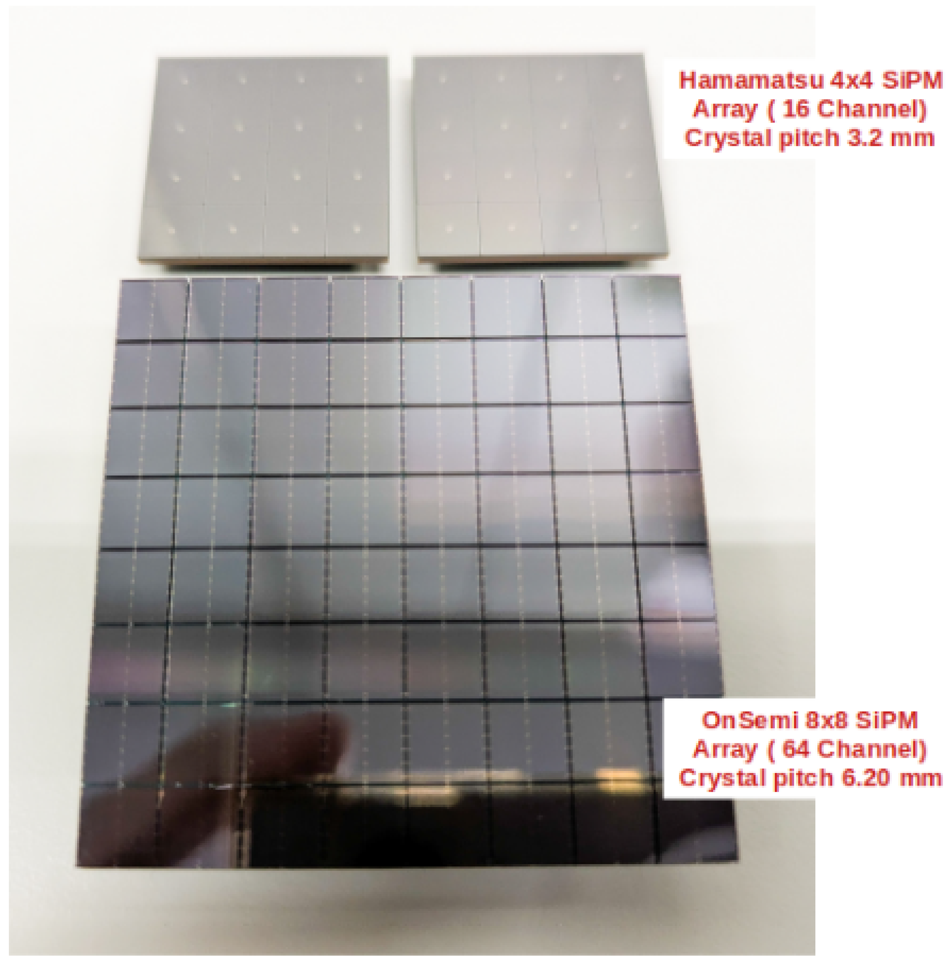

Figure 5: SiPM arrays acquired for experimental validation: Hamamatsu (top) and OnSEMI (bottom).

Conclusions

This work demonstrates that the proposed hybrid CNN-MLP architecture significantly outperforms the Li method, as well as standalone CNN and MLP models, in estimating the XY interaction position within monolithic crystal detectors. The hybrid approach provides measurable improvements in FWHM across all evaluated configurations and successfully mitigates the systematic edge effects inherent in analytical methods.

Furthermore, the simulation results validate the potential of this model as a robust tool for position reconstruction, supporting the selection of photodetectors with a 6 mm pixel size. This configuration optimizes system design by drastically reducing the number of readout channels without compromising spatial resolution.

Ongoing efforts are focused on further refining the neural network architectures to push the limits of prediction accuracy. Our immediate next steps include the experimental validation of these results using the recently acquired OnSEMI and Hamamatsu arrays, alongside the implementation of Z-component (Depth of Interaction) estimation to enable full 3D event reconstruction in the AIDER Compton Camera.

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