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A Feasibility Study on Neural Network Regression Models for Two-Dimensional Radioactive Source Localization Using PSF-SiPM Detection Systems

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1. Introduction

Plastic scintillating fibers (PSF) represent a significant advancement in radiation detection technology, offering superior spatial resolution, high detection efficiency, and remarkable flexibility in geometric configurations. Similarly, silicon photomultiplier arrays (SiPM) have emerged as compact, robust alternatives to traditional photomultiplier tubes, operating effectively at low voltage while maintaining high gain characteristics [1].

Despite these individual merits, the integration of PSF and SiPM technologies presents substantial challenges in low-dose measurement applications. The fundamental limitation manifests in elevated noise levels within the combined detection system, as PSF implementation necessitates high signal amplification while SiPMs inherently generate dark counts and crosstalk, limiting measurement precision in environmental radiation monitoring scenarios [2-4].

Artificial intelligence methodologies have demonstrated remarkable capacity for effective noise reduction and signal extraction in various scientific domains. Machine learning regression models, particularly those employing neural network architectures, demonstrate substantial capability in distinguishing genuine measurement data from randomly distributed noise patterns [5].

This research investigates the integration of AI regression techniques with PSF-SiPM detection systems to enhance two-dimensional localization of radioactive sources, employing a U-shaped PSF configuration with Cs-137 serving as the radiation source for system performance evaluation.

2. Methods and Results

2.1 Materials and Experimental Setup

The detection system integrates SCSF-78 (Kuraray) plastic scintillating fibers, ArrayJ-60035-64P-PCB (Onsemi) silicon photomultiplier arrays, and dual DT5202 (Caen) data acquisition systems connected via a central concentrator to a computer. The experimental apparatus comprises a 2 m^2 rectangular detection area (2 m × 1 m) surrounded by U-shaped PSFs with 0.25 m uniform spacing. This configuration yields two vertical and four horizontal PSFs, with both terminal ends connected to the DAQ system. The measurement protocol utilizes time-of-arrival (TOA) data recorded by the DAQ timestamp functionality, providing temporal position information for subsequent analysis.

2.2 Artificial neural network model construction

The position estimation implements a distributed regression approach using multiple fully-connected neural networks mapped one-to-one with individual PSF sensors. Each network estimates a single spatial dimension corresponding to its PSF orientation. The networks utilize time difference values computed by subtracting opposite-terminal TOA measurements from the same fiber. Neural network architectures incorporate optimized hidden layer configurations established through standard hyperparameter tuning protocols. Model optimization employs dropout regularization techniques to mitigate overfitting risks, while training utilizes the Adam optimizer algorithm for efficient convergence characteristics. Training data acquisition occurs through systematic measurement campaigns using the PSF-SiPM detection system, enabling the integration of individual position estimates for comprehensive two-dimensional source localization.

2.3 Results

Figure 1 presents time-difference histograms observed at two distinct source positions within the experimental area. Theoretical predictions suggest these histograms should exhibit Gaussian distributions, reflecting the statistical nature of photon detection processes in scintillator systems. However, empirical measurements reveal significant deviations from ideal Gaussian behavior, with distribution shapes showing position-dependent variations.

The observed non-Gaussian characteristics stem from multiple factors affecting signal quality. High amplification necessary for PSF signal processing introduces electronic noise, while inherent dark count rates and crosstalk in SiPM arrays further degrade signal fidelity. These noise sources alter the distribution shapes in the time-difference spectra.

The position-dependent variability of histogram characteristics makes conventional Gaussian fitting methods unreliable for source localization, validating the need for machine learning approaches to extract spatial information from complex time-difference distributions.

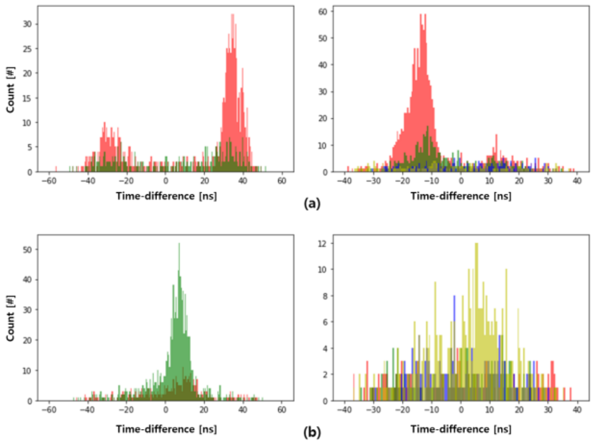

Fig. 1. Time-difference histograms for Cs-137 source-measured data at (a) (30, 45), (b) (195, 70) [cm] positions

Table 1 presents quantitative assessment metrics for the neural network-based position estimation system. The data lists multiple source positions and their corresponding estimation errors along both coordinate axes. The table includes Euclidean distance metrics, calculated as the square root of summed squared errors in both dimensions, providing a comprehensive scalar measure of localization accuracy.

Table 2 provides comparative analysis between artificial intelligence estimation methodology and conventional time-of-flight calculations. The comparison of actual source positions, neural network prediction errors, and time-of-flight computation errors enables direct performance evaluation between methodologies. The improvement ratio metrics quantify the enhanced localization precision achieved through machine learning approaches relative to traditional analytical methods. These comparative results demonstrate the effectiveness of neural network regression models in extracting positional information from noise-affected measurement data under challenging signal-to-noise conditions.

Table I: AI model-estimated source positions and their errors [cm]

Real positions	x-axis error	y-axis error	Estimation error
(5, 80)	2.437	-0.227	2.448
(30, 45)	5.392	-13.261	14.315
(80, 45)	7.010	-2.896	7.585
(155, 30)	11.174	-11.758	16.221
(195, 70)	2.559	-11.804	12.078

Table II: Comparison between AI model / calculation from measurement data-driven errors

Real positions	Error by AI model	Error by measurement	Improvement ratio [%]
(5, 80)	2.448	76.355	96.795
(30, 45)	14.315	53.461	73.223
(80, 45)	7.585	14.040	45.979
(155, 30)	5.713	57.740	90.106
(195, 70)	12.283	67.964	81.927

3. Conclusions

This investigation demonstrates the efficacy of artificial neural network regression models for enhancing two-dimensional radioactive source position estimation when implemented with plastic scintillating fiber and silicon photomultiplier detection systems. The distributed neural network architecture successfully extracts positional information from non-Gaussian time-difference distributions, overcoming signal degradation challenges inherent to these detector configurations. Quantitative performance metrics indicate superior localization accuracy compared to conventional time-of-flight calculation methodologies, particularly under challenging signal-to-noise conditions.

Future research will focus on comprehensive system optimization including neural network hyperparameter tuning, SiPM operating voltage adjustment, temperature control implementation, and signal processing parameter refinement to further enhance localization precision for low-dose radiation measurement applications.

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