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Deep Learning-Based Isotope Identification for Radiological Crime Scene Investigations Using Convolutional Neural Networks

Introduction

Accurate identification of radioactive isotopes is a critical task in nuclear security, environmental monitoring, and emergency response. Traditional gamma spectroscopy analysis relies on peak fitting, template matching, or expert-driven methods, which can struggle in low-resolution, low-statistics, and high-background environments. These challenges are particularly relevant when using portable NaI(Tl) detectors, which, despite their widespread field use, suffer from poor energy resolution compared to high-purity germanium (HPGe) detectors.

Advancements in deep learning offer a new approach to spectral analysis, leveraging convolutional neural networks (CNNs) to automatically extract spectral features and classify isotopes with high accuracy. CNNs, particularly in one-dimensional (1D) architectures, are well-suited for handling gamma-ray spectra directly, eliminating the need for extensive preprocessing.

This work presents a 1D convolutional neural network (1D-CNN) trained for isotope identification using simulated gamma spectra from a low-resolution 3″ NaI detector. The model is trained to classify 32 isotopes under realistic source strengths and background conditions, achieving a global classification accuracy of 0.94. Additionally, ongoing work is extending this approach to Cadmium Zinc Telluride (CZT) small-form-factor detectors, which offer higher resolution but present new challenges due to their small active volume and statistical noise.

Methodology

Data Generation and Simulation

To train and evaluate the proposed 1D-CNN, a dataset of simulated gamma-ray spectra is generated using Monte Carlo (Geant4) methods. The spectra are designed to reflect real-world measurement conditions by incorporating detector response, energy resolution, and background radiation levels.
The key parameters defining the dataset include:

- **Event count per spectrum:** Ranges from 5,000 to 100,000, simulating measurements from weak sources, short acquisition times, and varying detection distances.
- **Signal-to-(signal+background) ratio (S/S+B):** Randomized between 0.1 and 1.0, reflecting conditions from strong, isolated sources to highly obscured signals.
- **32 individual isotopes:** The dataset covers a broad spectrum of radionuclides relevant to nuclear security, medical, and industrial applications. Each spectrum is histogrammed into 1,024 energy bins covering an energy range of 0–3 MeV, which includes common gamma-ray emissions from these isotopes.

CNN Architecture

The 1D-CNN is designed to process raw energy spectra as one-dimensional signals, capturing the essential spectral features for classification. The model consists of:
- **Input layer:** Takes a 1,024-bin gamma spectrum as input.
- **Convolutional layers:** Multiple 1D convolutional layers with ReLU activation to extract spectral features.
- **Softmax output layer:** Produces a probability distribution over 32 isotope categories.

Training and Optimization

The model is trained using the Adam optimizer and a categorical cross-entropy loss function. The dataset is split into 60% training, 20% validation, and 20% testing, ensuring comprehensive evaluation.

Performance Metrics

Model performance is assessed using:
- Global classification accuracy (fraction of correctly classified spectra).
- Confusion matrix analysis to identify isotope misclassification patterns.
- Precision, recall, and F1-score for assessing model robustness across varying signal strengths and noise levels.

Results and Discussion

The 1D-CNN achieves a global classification accuracy of 0.94, demonstrating strong performance across a broad range of measurement conditions. The confusion matrix reveals that most misclassifications occur between isotopes with similar gamma emissions.

Ongoing work is extending this approach to small-form-factor CZT detectors, which provide superior energy resolution compared to NaI but introduce new challenges:
- Small active volume leads to lower event counts, requiring adaptation of the CNN to handle noisier, lower-statistics data.
- More precise peak structure in CZT spectra allows for finer isotope discrimination but necessitates retraining with high-resolution data.

Conclusion

This study demonstrates that 1D convolutional neural networks (1D-CNNs) can accurately classify gamma-ray spectra from a low-resolution NaI detector, achieving 94% accuracy even under challenging measurement conditions. The model's robustness to low counts and background variations makes it well-suited for real-time isotope identification in nuclear security and field applications. By enhancing isotope identification capabilities in low-resolution NaI and high-resolution CZT detectors, this approach helps bridge the gap between laboratory methods and real-world radiological security challenges. The development of portable, AI-driven radiation detection systems has the potential to improve border security, emergency response, and illicit trafficking prevention.

Workshop topics

Applications

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