Simulation and Optical Test Validation for Single Crystal Detector based Gamma Source Localization and Identification

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Introduction

The localization and identification of unknown gamma sources is a crucial aspect of radiation safety, nuclear waste management, decommissioning of nuclear facilities, nuclear forensics, and homeland security. The conventional localization methods often rely on mechanical or electronic collimation, such as position-sensitive pixelated arrays with coded apertures [1], or systems incorporating single-crystal detectors with rotating collimators [2]. However, these techniques often require expensive detection systems with complex readout electronics and long acquisition times, respectively.

Typically, gamma localization applications involve the detection of a small number of radiation sources within a larger field of view. Hence, alternative detection technique such as L1-minimization [3] can be employed to achieve source localization with a single-crystal detector which exploits the sparsity of sources in the scene. This offers a more efficient solution in terms of both hardware complexity and data acquisition time.

This paper presents a simulation setup using the GEANT4 toolkit [4] for data generation and performance validation of the L1-minimization-based gamma source localization method along with experimental verification through an optical test setup to demonstrate the efficacy of this approach in real life scenarios.

Simulation Setup

In the L1-minimization technique, the goal is to minimize the following equation (1)

$$\underset{x}{minimize}\ \frac{1}{2}||y-\phi x||_2^2 + \tau||x||_1 \qquad (1)$$

Where y is the measurement vector, x represents the scene, ϕ is the measurement matrix, and τ represents the relative strength of the L1 norm. The measurement matrix plays a crucial role in spatially encoding the scene onto the detector. In this technique, a series of randomized patterns (masks) are used to modulate the detector's response towards the radiation image. These patterns construct the measurement matrix and detector response provides the measurement vector.

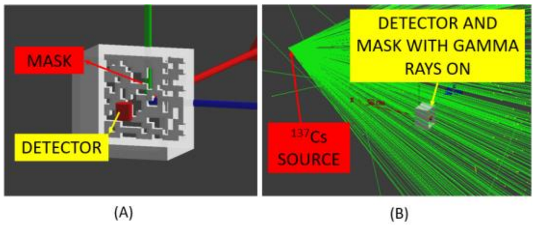

Fig.1 (A) Detector and mask configuration in GEANT4 environment, (B) Detector and mask exposed to gamma rays from an ^{137}Cs source kept at a distance of 2 m from the detector plane.

For the simulation setup, a total of 45 random binary matrices, each of size 15x15 with 50% opacity, are generated using a uniform distribution. These matrices were subsequently transformed into solid physical masks using CAD software and imported into the GEANT4 simulation environment. A 4-cc cylindrical NaI detector is used as a gamma detector.

In the simulation, a specific radioisotope is considered using an ion table that defines the atomic number and mass number of the isotope. The gamma source is positioned at the center of the field of view (FOV) of the masks, as shown in Fig 1. The energy deposition within the detector volume is recorded for each mask configuration. An appropriate energy window is applied on the data of each mask to extract the event count for further analysis. In this way, this method can simultaneously localize and identify the source by selecting a proper energy widow (photo peak).

The measurement matrix is constructed by reshaping each binary mask into a one-dimensional vector and vertically concatenating these vectors to form the complete matrix. The reconstructed image of the ^{137}Cs source location, as obtained from the data for 45 masks, is shown in Fig. 2. This measurement data corresponds to about 20% of the data for an 15x15 pixel image

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plane, thus indicating the efficiency of this technique.

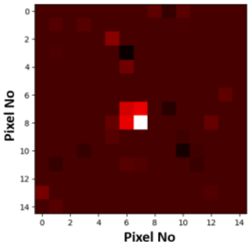
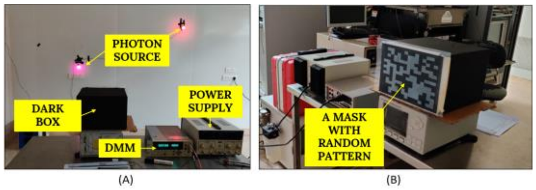


Fig. 2 Reconstructed image of ^{137}Cs placed at the center of the mask's FOV.

Optical test setup

The simulation results are validated using an optical test setup as an intermediary step before the fabrication of the actual detector module. In this setup, a light-dependent resistor (LDR) array is used as the detector (summation response used to mimic the single crystal detector), and patterned masks are printed (B&W) on transparent sheets. The experiment utilizes the same set of 45 masks as used in the simulation.



(A) (B)

Fig. 3 (A) Experimental setup for optical test. (B) Random pattern mask with the dark box.

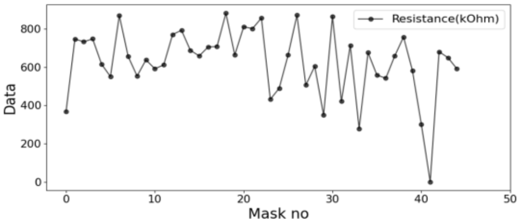


Fig. 4 Variation in total LDR resistance with mask number in the optical experimental setup.

The detector array is enclosed in a customized dark box with an open face on one side, where the mask is positioned. Two light sources are positioned within the FOV of the mask at approximately 2m from the detector plane, as shown in Fig. 3. The total resistance value of the LDR array for each mask set, as measured using a digital multimeter (DMM), provides the measurement vector. Variation in the total resistance of the LDR array with mask number is shown in Fig. 4.

Results

In the optical experiment, the L1-minimization was applied on the acquired measurement vector to reconstruct the light source location. This reconstructed source image was subsequently fused with the optical image of the scene to illustrate the accuracy of this technique as shown in Fig. 5.

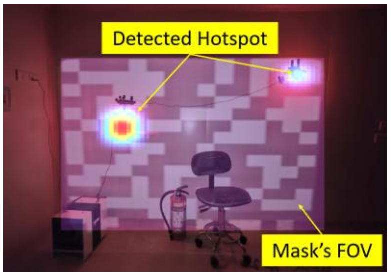


Fig. 5 Blended image, combining the scene photograph with the reconstructed photon image.

Conclusion

In this work, the effectiveness of the L1-minimization method for gamma source localization utilizing the sparse nature of the real-life situation is studied. The method has been validated through Monte-Carlo simulation data and duly supported with an optical experiment. This study has led to the focused efforts for the development of a gamma source localization and identification instrument using L1-minimization technique.

References

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