Feasibility Study of an AI-Assisted Radiation Source Localization and Tracking System for Enhanced Nuclear Security

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Keywords : gamma-ray imaging system, Artificial Intelligence, nuclear security

1. Introduction

Detection of nuclear and radioactive materials in imported cargo and at public facilities is a critical for national security. Current radiation detection devices, such as Radiation Portal Monitors (RPMs) and handheld survey meters, primarily operate on a total dose alarm principle. This approach is inherently limited by its inability to provide spatial information, making it a time-consuming and often inaccurate process to pinpoint the exact location of a radioactive source, especially in complex, dynamic environments like ports, airports, and urban areas. This limitation not only poses a safety risk to operators but also a significant security vulnerability. To address this challenge, we propose a novel approach that integrates advanced gamma-ray imaging with AI-driven object tracking to enable real-time localization and tracking of moving radioactive sources. This study presents a comprehensive feasibility analysis of such a system, demonstrating its potential to provide a foundational paradigm shift in radiation security by transforming reactive alarms into proactive, visual-based threat assessment.

2. Materials & Methods

The proposed system, named portable Fast Gamma Imager (pFGI), is designed to rapidly identify and localize radioactive materials under the most challenging environmental conditions. The pFGI employs a high-sensitivity imaging module that leverages a hybrid gamma imaging technique. This innovative approach synergistically combines the established methodologies of Compton imaging and coded-aperture imaging to achieve a superior signal-to-noise ratio (SNR) and real-time performance that surpasses conventional systems. The hybrid imaging is not a simple superposition but is implemented through a pixel-wise multiplication of the images meticulously reconstructed from each method.

The detector module is a monolithic scintillation detector. The detector consists of a NaI(Tl) crystal, chosen for its optimal light yield, cost, and decay time, with a large area of 14.6×14.6cm^2. This crystal is coupled to a photosensor array of nine square photomultiplier tubes (PMTs) in a 3×3 configuration. For Compton imaging, two of these detectors are placed at the front and back of the system. Additionally, to enable coded-aperture imaging, a coded-aperture mask is precisely positioned in front of the detector assembly, allowing the system to perform a passive imaging technique that is highly effective for low-energy gamma rays.

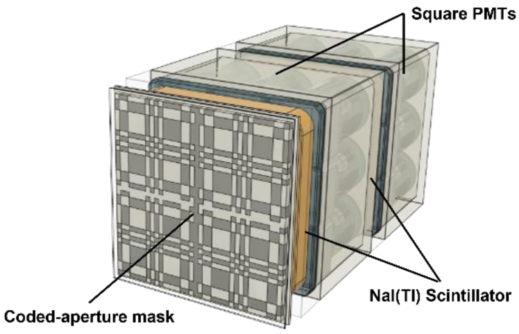

Fig. 1. Configuration of the pFGI Detector Module.

In this study, to acquire peripheral geographical information for object detection and object-specific image space settings, an RGB-D camera (D455, Intel, CA, USA) was used. This camera provides RGB images of the surrounding environment and depth images containing distance information to objects. For real-time object detection and tracking, the YOLOv8 algorithm was employed. The system's operation involves first detecting objects in the RGB image and acquiring their distance from the depth image. Using this information, an object-specific image space is set. The system then tracks object displacement ($\Delta\overrightarrow{P_{obj}}$) between successive frames. An accumulated radiation image is translated by $\Delta\overrightarrow{P_{obj}}$ and combined with the current frame's radiation data, which is then superimposed with the current RGB image showing object detection results.

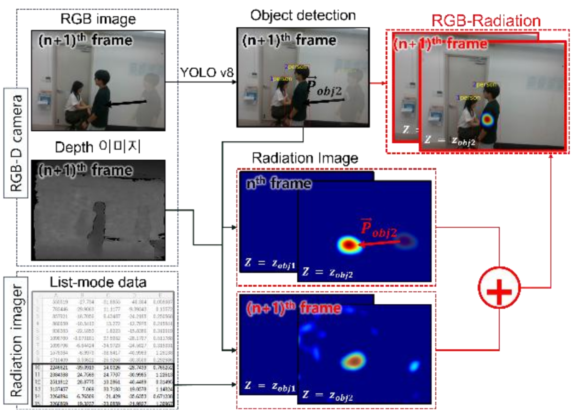

Fig. 2. AI-Based Object Tracking and Radiation Image Visualization Technique.

To verify the developed technology, the Geant4 Monte Carlo simulation toolkit (v10.07.p02) was utilized. A scenario was simulated where a person carrying a ^{137}Cs point source moved approximately 7.2 m in an environment with four other people, which was pre-recorded for 12 seconds with the RGB-D camera. The visualization performance of the moving source was then compared before and after applying the developed technology.

3. Results

The experimental results show a significant improvement in performance. As show in Fig. 3, at a dose rate of 0.028 μSv/h, the pFGI achieved a localization time of only 0.87 seconds, which is approximately 95 times faster than a commercially available imager (Polaris-H420) at 83 seconds. Even at a lower incremental dose rate of 0.0005 μSv/h, the pFGI successfully imaged the source location within 300 seconds. These findings underscore the capability of pFGI for rapid and accurate detection, even in low-dose-rate scenarios. The results also highlight a clear distinction in performance compared to other detectors. The pFGI demonstrates a consistently faster localization time across various dose rates, especially in low-dose-rate conditions, solidifying its position as a superior solution for real-time security applications.

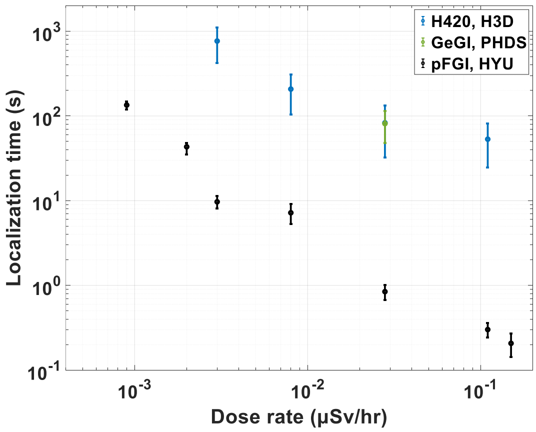

Fig. 3. Comparison of localization time between the pFGI and the commercial gamma imager (H420).

The AI-assisted system also showed a clear ability to distinguish between individuals carrying a radioactive source and those who are not. Specifically, when a person is not carrying a radioactive source (as depicted in Fig. 4. a-e), the maximum value of the reconstructed radiation image appears outside the person's bounding box. Conversely, when the person is carrying a radioactive source (as shown in Fig. 4. f), the maximum value of the radiation image is located precisely within the bounding box of the person. This indicates that the developed technology can precisely identify the source carrier, thereby offering a significant advantage over conventional systems that only trigger a general alarm.

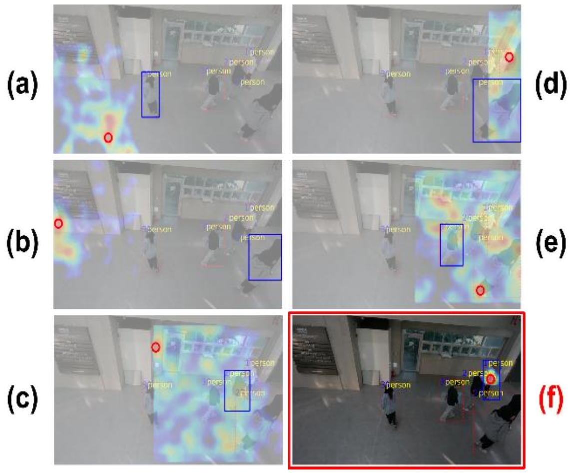

Fig. 4. Visualization and tracking of movingrRadioactive material carriers.

3. Conclusions

The results of this feasibility study demonstrate that a hybrid gamma imaging system, particularly the pFGI, can quickly and accurately localize radioactive materials. The development of such a high-speed system addresses the critical limitations of existing radiation detection devices, which lack robust imaging capabilities. By providing a real-time visual representation of radioactive sources, the pFGI is expected to streamline customs and security procedures, and more importantly, significantly mitigate the risk of nuclear and radioactive material transport. This research establishes a solid foundation for a new generation of intelligent radiation security systems that can transform the paradigm from reactive alarms to proactive, visual-based tracking. Further development will focus on integrating AI for automated identification and tracking of moving objects, paving the way for full commercialization.

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