Radioactive source localization in 3D using a coded aperture device under near field irradiation with the aid of convolutional neural networks

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Coded Aperture γ-cameras, which have been utilized for over three decades in diverse fields such as astrophysics, nuclear facility decommissioning, and nuclear medicine, play a crucial role in imaging radioactive source distributions. These devices capture the spatial coordinates of γ-emitters within their field of view by leveraging the pattern of a coded-aperture mask. This mask projects a shadowgram onto pixelated detectors, which is essentially the coded aperture projection created by the differential gamma photon counts filtered through the mask's opaque and transparent regions.

Traditionally, the processing of shadowgrams involves correlating them with a digital matrix that mimics the mask pattern. The correlation matrix generated from this process highlights a peak value that accurately indicates the direction from which the radioactive source originates.

In this work we introduce the use of convolutional neural networks (CNNs) for the analysis of these images under near-field irradiation conditions, making it particularly suitable for medical applications.

With this approach we are able not only to identify the direction but also to estimate the three-dimensional position of the source in spherical coordinates. This includes the computation of the θ (theta) and φ (phi) angles, along with the magnitude of the R vector. This 3D localization capability enhances the accuracy and utility of γ-cameras, especially in environments where precise spatial resolution is critical, such as in targeted radiation therapies and diagnostic procedures in nuclear medicine. This methodology significantly refines the potential to detect and analyze radioactive sources in a detailed and spatially complex manner.

In the experimental setup, we have been using a modified uniform redundant array (MURA) mask constructed with a very simple method, which we call it "Not Two Obscures Touching (NTOT) MURA" [1]. It is placed in front of a CdTe pixel detector with total active area 44 x 44 mm^2 and pixel pitch 350 μm. The recording rate is 27 frames/sec. The energy-spectrum resolution of each pixel is 3 to 4 keV FWHM for the 141 keV photo-peak of ^{99m}Tc. The NTOT MURA mask has been placed parallel to the CdTe plane at 2 cm distance. Its basic pattern consists of 19x19 elements, the element pitch is 1958 μm and the total elements of the mask are 37x37. The distance of a point source from the detector for which an optimum Point Spread Function (PSF) is obtained is about 310 mm and it depends on the element pitch.

In this research, we have developed a deep learning model using a Convolutional Neural Network (CNN) architecture. The model features an input layer, two 2D Convolutional layers designed to extract features from recorded shadowgrams, a Max pooling layer for reducing data dimensionality, two dense layers, and an output layer. We trained the model on a dataset of 7,200 shadowgrams, which were generated through simulations using a custom, fast simulation tool [1]. This tool simulated shadowgrams based on sources placed at 7,200 random positions within the field of view (FOV), and at distances up to 100 cm from the detector plane.

To prevent overfitting, we utilized an independent set of 2,400 shadowgrams for cross-validation during the training phase. We assessed the model's performance using another separate set of 2,400 shadowgrams, with results detailed in Figures 1-3. A key feature of our approach was incorporating the magnification of mask elements into the feature space to estimate the distance between the source and the detector plane.

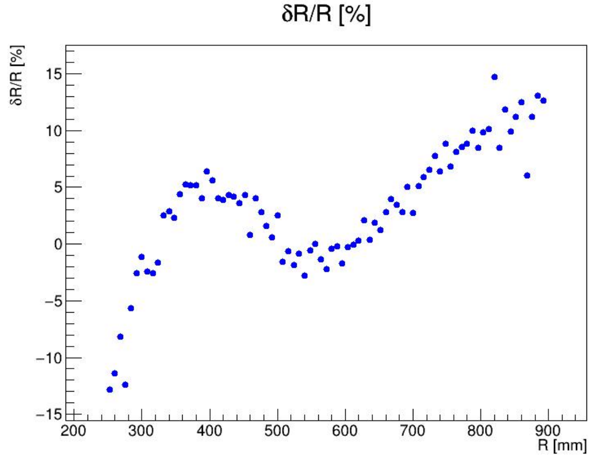

Figure. 1. Distribution of the relative error in estimating the distance R of the source as a function of the real distance R.

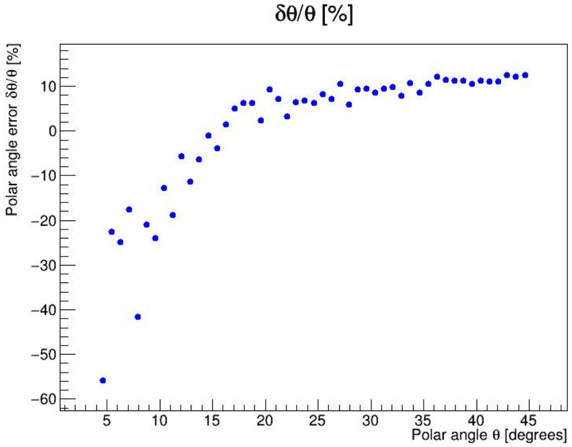

Figure. 2. Distribution of the relative error in estimating the polar angle θ of the source as a function of the real polar angle θ.

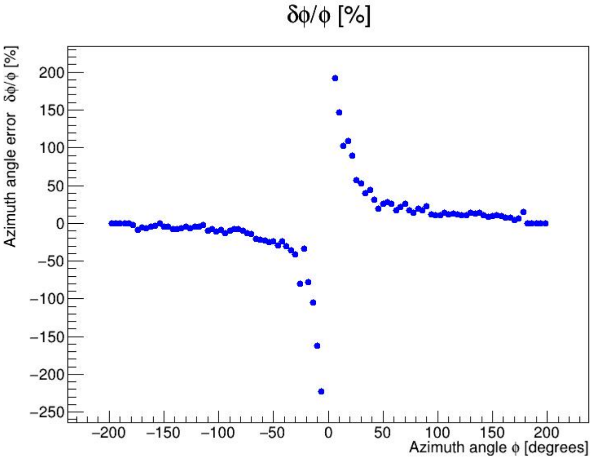

Figure. 3. Distribution of the relative error in estimating the azimuth angle φ of the source as a function of the real azimuth angle φ

Figure 1 illustrates that the accuracy of estimating the source's distance is within 5%, or less for distances ranging from 300 mm to 700 mm from the detector. Beyond this distance range, the convolutional neural network (CNN) becomes less reliable in estimating the source's distance. This reduced accuracy is likely due to the inadequate magnification of the mask elements on the detector plane. This observed behavior corresponds with the correlation method used to determine the 3D spatial coordinates of radioactive sources. According to the correlation method, the optimal distance for a 19x19 MURA mask with an element pitch of 1958μm is 310mm.

Figure 2 demonstrates that the estimation of the polar angle is accurate to within 10% across the range of 15° to 45°. Furthermore, Figure 3 shows that the azimuth angle is estimated with an accuracy of less than 10% for most of its range. However, there is an increase in relative error when estimating very small azimuth angles.

Finally, the performance of the algorithm will be evaluated with data sets of experimental shadowgrams taken using cylindrical extended sources of ^{99m}Tc with a diameter of 1 cm or 2 cm. The experimental evaluation is a work in progress.

[1] Editor: Krzysztof (Kris) Iniewski, Springer 2022. Book: Advanced X-ray Detector Technologies. Chapter: Coded Aperture Technique with CdTe Pixelated Detectors for the Identification of the 3D Coordinates of Radioactive Hot-Spots. https://doi.org/10.1007/978-3-030-64279-2

[2] I. Kaissas, C. Papadimitropoulos, C. Potiriadis, K. Karafasoulis, D. Loukas, and C.P. Lambropoulos, 2017. Imaging of spatially extended hot spots with coded apertures for intra-operative nuclear medicine applications. Journal of Instrumentation, 12(1), art. no. C01059.