NEUTRON-PHOTON COMPUTED TOMOGRAPHY OF CARGO CONTAINERS IN A CONE BEAM CONFIGURATION

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ABSTRACT
Radiation techniques are important for nondestructive testing of large items, e.g. for locating manufacturing defects in industrial products or for inspecting contents of cargo containers. Computational studies of an imaging system based on high-energy x-rays (6 and 9 MeV) and neutrons (2.5 and 14 MeV) were carried out. Both radiation probes were combined in the single system and collimated as cone beams in the same source-container-detector configuration. Objects of different shapes and materials were placed inside the container, and the latter was rotated about its central axis between scans. Reconstruction using computed tomography projection data from just a few angles was performed for both sources individually and then utilized for visualizing the container contents. Based on inherent differences between neutron and photon interactions with matter, it was possible to discriminate between materials inside the container.

KEYWORDS
Neutron imaging, photon radiography, computed tomography

1. INTRODUCTION
The x-ray radiography is a well-known approach for object shape analysis in nondestructive testing applications. To accomplish material identification, the dual-energy x-ray radiography is a widely used technology. The ratio of attenuation coefficients under two energies is a signature shown to have advantages due to the penetration ability of high-energy photons through dense objects as thick as 380 mm of steel. However, the study of limits suggests that material discrimination under different scene settings in the cluttered environment could be problematic [1]. Besides, discrimination of low-density organic materials using 2D projections of transmitted x-rays is inefficient [2] for complex objects that are composed of low- and high-density materials of different thickness. The neutron-based systems are more sensitive to low-z materials, such as hydrogen-rich compounds, and materials with large neutron reaction cross-sections. The computed tomography (CT) resolves the problems of 2D projections and object reconstruction in the cluttered environment [3, 4].

A computed tomography method which utilizes two radiation sources, neutrons and photons, is considered for shape reconstruction and material classification. Using two different sources for the radiography, rather than two identical sources with different energies, could enable better visualization of objects and material discrimination based on the ratio of numbers of transmitted photons and neutrons [5]. Because CT in general is time consuming, a sparse-view tomography is a viable approach. However, reducing the number of scans at different angles leads to degradation in the reconstructed 3D images. The iterative reconstruction (IR) methods were shown to outperform its classical counterparts under the sparse-view architecture and noisy conditions [6, 7]. These methods were applied to the combined neutron-photon CT in a cone beam configuration.

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2. COMPUTATIONAL MODEL OF NEUTRON-PHOTON TOMOGRAPHY SYSTEM

The neutron-photon CT system was studied using the Monte Carlo radiation transport code MCNP5 [8]. The computational model is shown in Fig. 1. The cone beams of neutrons and photons were set up to irradiate a model container. A detector array was set up to tally the neutrons and photons being transmitted through the object. Two scenarios were used, each consisting of a (50×50×50) cm³ aluminum container with 3-cm-thick walls and a set of objects of different size, shape and composition placed inside. The distance from the source to the nearest surface of the container was 249 cm. The detector array was placed in 30 cm away from the back wall of the container.

Fig. 2 shows a scheme of the container model (shapes, orientation, and materials of the objects). The model was intended to study the ability of tomographic reconstruction to represent shapes such as sphere, cone, L-shape, parallelepiped, to test the separation of high-z and low-z materials. To test the reconstruction technique on its ability to separate objects under the sparse-view conditions, the model includes the 1-mm gaps between parallel faces of objects 2, 3, 4, and the 1-cm gaps between objects 5, 6, and 8.

![Figure 1. Neutron-photon system scheme.](image1)

![Figure 2. Objects placed inside the container.](image2)
The model includes the following objects placed inside the container: (1) cone, 6-cm in diameter and 8-cm-high; (2) parallelepiped, 8 cm (L) × 9.9 cm (W) × 10 cm (T); (3) parallelepiped, 7.9 cm (L) × 6 cm (W) × 10 cm (T); (4) and (6) are parallelepipeds, each 8 cm (L) × 6 cm (W) × 10 cm (T); (5) parallelepiped, 7 cm (L) × 6 cm (W) × 10 cm (T); (7) irregular body, 10.2 cm × 13.6 cm × 8.7 cm × 6 cm; (8) parallelepiped, 8 cm (L) × 9 cm (W) × 10 cm (T); (9) parallelepiped, 6 cm (L) × 6 cm (W) × 10 cm (T); (10) parallelepiped, 10 cm (L) × 6 cm (W) × 10 cm (T); (11) and (12) are (5) parallelepipeds, each with dimensions 6 cm (L) × 6 cm (W) × 5 cm (T).

The flux image radiography (FIR) tally was utilized to set up a rectangular radiation detection grid which treats each quadrant as a ‘pixel’ of the imaging array. The array was defined for a 92 cm by 92 cm area (100×100 pixels). The transmitted radiation flux tallied in this array formed the 2D projection of transmission data for the container recorded for different system orientations using the rotational motion of the container. To obtain radiographic projections, the container was rotated about its vertical axis with 5° angular increments.

3. CT RECONSTRUCTION AND MATERIAL ANALYSIS

The CT reconstruction of 3D scenes in the model was carried out using the IR methods [6, 7] and the traditional FDK [9]. Two regularizers were used for the reconstruction: the total variation (TV) and the wavelet coefficients (W). The TV is appropriate if the reconstructed data are piecewise constants or have low total variations throughout the image [10, 11]. Recently wavelet regularization has been used for denoising, and also for solving more general problems like the inverse problem [12, 13].

The reconstruction errors were the following: 9.86% for FDK, 8.98% for IR+TV and 9.13% for IR+W for neutron imaging only. The error was calculated as a percentage of voxels lost/added to the objects’ actual voxels. The errors of reconstruction of 6-MeV photon images were calculated only for high-z objects due to the almost complete transmission of 6-MeV photons through low-z materials (as shown in Fig. 3): 8.14% for FDK, 6.69% for IR+TV and 8.87% for IR+W. The error values increase when the number of angles in the sparse view is changed to 18, corresponding to the increment of 10 degrees. The reconstruction errors using the neutron source only are 38.1% for FDK, 29.7% for IR+TV and 33.5% for IR+W. Due to the superiority of the IR+TV method, it was selected for the object visualization.

Reconstruction results are shown in Fig. 3 for 6-MeV photons and in Fig. 4 for 2.5-MeV neutrons. It can be concluded that the neutron images represent shapes of objects of low-z and high-z materials equally well under the sparse views; the IR+TV is capable to capture main geometric features of objects and separate closely positioned objects. The parameter \( R_{p/n} \) is the ratio of photon transmission \( T_p \) to neutron transmission \( T_n \). Let us consider the material signatures defined as \( R_{p/n} \) plotted versus \( T_n \) values per object’s voxel. The plots presented in Fig. 5 shows the signatures for high-z materials and low-z materials. It shows that the decoupling of materials such as graphite and boron is uneasy due to the large neutron capture cross section of the latter. It was observed that partitioning the materials based on such signatures promises better accuracy when the difference in atomic numbers of materials is greater than 6.

Mean and standard deviation values for these distributions were determined. Considering the mean values as a library of materials of unknown objects under inspection, the distances in 2D space of signatures to mean values in the library were calculated; a minimum value of the distance establishes the material of the object under inspection. The material discrimination accuracy for the container model using these signatures was evaluated as 85% for high-z materials and 70% overall. For known objects/materials a type of the library can be obtained through experimentation.
Figure 3. 3D visualization of IR+TV reconstruction using the 6-MeV photon source.

Figure 4. 3D visualization of IR+TV reconstruction using the 2.5-MeV neutron source.

Figure 5. Signatures of (a) high-z materials and (b) low-z materials.
Applied to the voxels of objects that were found based on the shape reconstruction from neutron transmission this approach leads to a noisy classification of materials which after the post-processing based on majority voting per object yields the result shown in Fig. 6.

4. CONCLUSION

The application of the combined neutron-photon tomography was studied for the object’s shape reconstruction and characterization of materials. A dual-radiation system consisting of neutron and photon sources collimated to generate cone beams and a model container was simulated using the MCNP5 code. The iterative algebraic reconstruction method with the TV regularization was utilized for reconstruction of object’s shapes based on the 2D radiographs obtained at different angles.

The material signatures defined as the photon-to-neutron transmission ratio versus the neutron transmission per voxel in the reconstruction space were employed for material identification. The latter has demonstrated a better accuracy of identification of materials when a simple clustering method based on the statistics of the library of materials was employed. Future research efforts include various aspects ranging from the CT reconstruction to the practical system design.

REFERENCES