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Investigation of innovative radiation imaging method and system for radiological environments

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ABSTRACT

We have developed a novel imaging method that can be applied to most applications in the field of radiological environment imaging. It resolves either two-dimensional (2D) or three-dimensional (3D) distributions of radioactive sources in applications for homeland security, environmental monitoring, radiation contamination monitoring, baggage inspection, nuclear power plant monitoring, and more. The proposed imaging method uses a simple detector configured as a radiation-counting detector with spectroscopic capabilities. The detector module consists of two components: a flat field-of-view (FOV) collimator with a 30° FOV opening and a typical single-channel radiation detector made of a 2 in.×2 in. NaI(Tl) scintillator coupled to a 2 in photomultiplier tube (PMT). This simple detector module makes it possible to develop a cost-effective imaging system and provide design freedom in extending the system configuration to include one-dimensional (1D) or 2D detector-array shapes to meet the needs of various applications.

One of most distinctive features of the new imaging method is that it uses only a pair of 2D projections to obtain a 3D reconstruction. The projections are measured by the proposed detector module at two positions orthogonal to one another; the measured projections are manipulated to enhance the resolution of the reconstructed 3D image. The imaging method comprises several steps performed consecutively: projection measurement, energy re-binning, projection separation, resolution and attenuation recovery, image reconstruction, and image consolidation and quantitative analysis. The resolution and attenuation recovery step provides the most distinctive and important processing by which the poor quality of projection data is enhanced. Such poor quality is mainly due to the use of a simple detector with a wide-opening flat FOV collimator.

Simulation and experimental studies have been conducted to validate the proposed method. In this investigation, we demonstrated imaging of 3D space, which is the most general and fundamental task in the field of radiological environment imaging. The experiments show quite promising results. In addition, the method is able to provide quantitative information about each distribution, including isotope identification, activity concentration, and the size and shape of radiation sources. Our future studies include employing other detector modules and collimators and developing systems for other applications, such as container truck and conveyor inspections.

1. Introduction

The visualization of the distribution of radioactive sources has attracted attention in the field of assessment of radiological environments. Its representative applications include homeland security, environmental monitoring, radiation contamination monitoring, baggage inspection, and nuclear power plant monitoring. Several research groups have been conducting active research, development, and commercialization efforts involving such imaging systems [1–7]. For instance, the RadScan gamma imaging system, proposed by BIL Solutions Ltd. (UK) [2], consists of an NaI scintillator crystal coupled to a photomultiplier tube (PMT) and a custom-designed tungsten-alloy collimator. The collimator assembly offers pan and tilt motions in order to generate two-dimensional (2D) gamma images. The system uses a charge-coupled device (CCD) to visualize the intensity distribution of gamma-ray images in a visible CCD image. The RadCam series offers commercially available products developed by Radiation Monitoring Devices, Inc. (MA, USA) [3,4]. This imager consists of a position-sensitive PMT coupled to a CsI(Na) scintillator and tungsten-coded aperture mask. The gamma-ray image is superimposed on a visible

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image captured by a high-resolution CCD. Another commercial product, CARTOGRAM, using a CCD-based gamma detector and coded aperture collimator, has been proposed by Oliver Gal's group [5,6]. In recent years, this group presented GAMPIX [7], a new generation gamma camera, which uses a Timepix pixelated chip, hybridized with a 1 mm thick CdTe substrate, and a coded aperture to increase compactness and improve sensitivity.

Although these systems allow intuitive determination of the distribution of radiation sources, they present the critical limitations of low sensitivity and poor spatial resolution, limiting their practical qualifications for use as radiological environment imaging systems. These limitations are caused mainly by collimation and relatively small imaging detectors, which must cover wide and distant imaging targets. In addition, the conventional technology would prove unreasonably expensive when expanded to large-scale installations. To address the limitations found in conventional gamma-imaging methods and systems used in radiological environment imaging, we have developed a novel imaging method using a pair of orthogonal projections measured by two detectors simply configured. To increase sensitivity, a wide open collimator, the so-called flat FOV collimator, is employed. Spatial resolution degradation incurred by opening the collimator is recovered by using Gaussian deconvolution algorithms.

The proposed method enables: 1) easy and cost-effective expansion for large-scale imaging applications; 2) significant and simultaneous improvements in both sensitivity and resolution; and 3) quantitative analysis, including isotope identification, activity concentration estimation, and 3D positioning information of radioactive source locations. In this paper, we describe the details of our proposed imaging method, simulations, and experimental studies. The concept and application examples of the proposed method also appear in our patent application [1].

2. Materials and methods

2.1. Problems of conventional systems: cost effectiveness, sensitivity, and resolution

Conventional systems and methods for radiological environment imaging employ typical gamma-emission imaging techniques used in the field of nuclear medicine. In general, the imaging system typically consists of a collimator, scintillator, and one or more photo sensors. Although the imaging principle and detector configuration are similar, the imaging conditions for radiological environments are quite different from those encountered in nuclear medicine when imaging a human being. For example, environment imaging covers a much broader area, and the distance between a target and a detector is substantially greater than what one encounters when imaging a person. Typically, environment imaging is performed using a detector placed a few tens of meters to a few meters away from a target. Further, gamma-energy measurements in radiological environment imaging range up to a few MeV. In contrast, a detector in nuclear medicine is configured to scan close to the contours of a human body and to capture gamma rays with energies ranging up to a few hundred keV. Because of such different imaging conditions, conventional environment imaging systems, which require heavy collimation, use relatively small detectors in comparison to the imaging target. These detectors, acquiring radiation from long-distance sources, pose some fundamental limitations, such as inferior sensitivity and spatial resolution. In addition, conventional technology is unreasonably expensive when the imaging system requires expansion for imaging large-scale objects, such as containers and trucks at border-control checkpoints.

2.2. Detector module

If we define our imaging problem as searching for "hot spot"-like radioactive source distributions in a target environment, it is possible to develop imaging methods and systems that deviate from the known requirements of conventional gamma-ray imaging methods and systems. Accordingly, an imaging method that requires substantially less sampling and fewer measurements, for which a simplified detector configured for hot-spot imaging may be used, may be provided to match various system configurations. The essential components and parameters for prior-art imaging detectors, such as a collimator, intrinsic spatial resolution, and sampling requirements, are no longer essential for conducting hot-spot imaging. This paper refers to such a detector as a non-imaging detector; it consists of a single slab of scintillator with a PMT. As the name implies, it is not capable of generating meaningful images by itself.

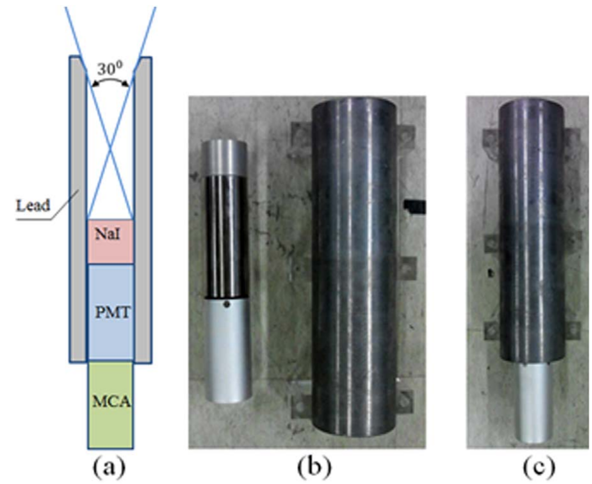

Fig. 1. Detector module. (a) Graphical representation of the proposed detector module. (b) Radiation detector (left) and collimator (right). (c) Assembled detector module.

The non-imaging detector used in the proposed method consists of simple two components: shielding and a typical single-channel radiation detector, as shown in Fig. 1(a). The wide opening hole by the shielding, referenced in this paper as a flat-field collimator, enables significant sensitivity gains. In addition to offering large increases in sensitivity, an additional advantage of using such a simple detector arises when using it to create cost-effective 1D or 2D array detectors for various applications. The intrinsic spatial resolution degradation caused by a wide opening hole is recovered by Gaussian deconvolution based a resolution recovery algorithm in the image-reconstruction stage. This algorithm will be described in details in succeeding chapters.

Fig. 1(b) and (c) show the detector module used in our simulation and experiment. The shielding part has an opening diameter of approximately 50.8 mm and is made of 20-mm-thick lead. The component providing the shielding confines the FOV of the radiation detector to 30°. The second component, depicted on the left in Fig. 1(b), is a radiation detector made of a 2 in.×2 in. NaI(Tl) scintillator coupled to a PMT and a multi-channel analyzer (MCA) (Nucare, Korea). The NaI detector module is inserted into the shielding part as shown in Fig. 1(a) and (c). In our preliminary experiment, a single detector module, shown in Fig. 1(c), is mounted on a pan-tilt device which is secured to a tripod and provides raster scanning.

2.3. Imaging method using the non-imaging detector

Fig. 3 presents a flow chart outlining the steps of a radiation imaging method: projection measurement, energy re-binning, projection separation, resolution and attenuation recovery, image reconstruction, and image consolidation and quantitative analysis. The most distinctive additional steps, compared to those in conventional image reconstruction, are the projection manipulation steps, namely, projection separation followed by the resolution and attenuation recovery