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Gamma-Ray imaging for nuclear security and safety: Towards 3-D gamma-ray vision

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ABSTRACT

The development of portable gamma-ray imaging instruments in combination with the recent advances in sensor and related computer vision technologies enable unprecedented capabilities in the detection, localization, and mapping of radiological and nuclear materials in complex environments relevant for nuclear security and safety. Though multi-modal imaging has been established in medicine and biomedical imaging for some time, the potential of multi-modal data fusion for radiological localization and mapping problems in complex indoor and outdoor environments remains to be explored in detail. In contrast to the well-defined settings in medical or biological imaging associated with small field-of-view and well-constrained extension of the radiation field, in many radiological search and mapping scenarios, the radiation fields are not constrained and objects and sources are not necessarily known prior to the measurement. The ability to fuse radiological with contextual or scene data in three dimensions, in analog to radiological and functional imaging with anatomical fusion in medicine, provides new capabilities enhancing image clarity, context, quantitative estimates, and visualization of the data products. We have developed new means to register and fuse gamma-ray imaging with contextual data from portable or moving platforms. These developments enhance detection and mapping capabilities as well as provide unprecedented visualization of complex radiation fields, moving us one step closer to the realization of gamma-ray vision in three dimensions.

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1. Introduction

Gamma-ray imaging is well established in many fields, including medicine, biomedical research, and astrophysics. It also has found applications in nuclear security and safety providing means to detect, localize, and characterize nuclear materials in a range of uses and environments. Of general concern for security is the misuse of radioactive materials as utilized in industrial and medical applications. Of particular concern is the safeguarding and proliferation of so-called Special Nuclear Materials (SNM), such as enriched ^{235}U or ^{239}Pu, and

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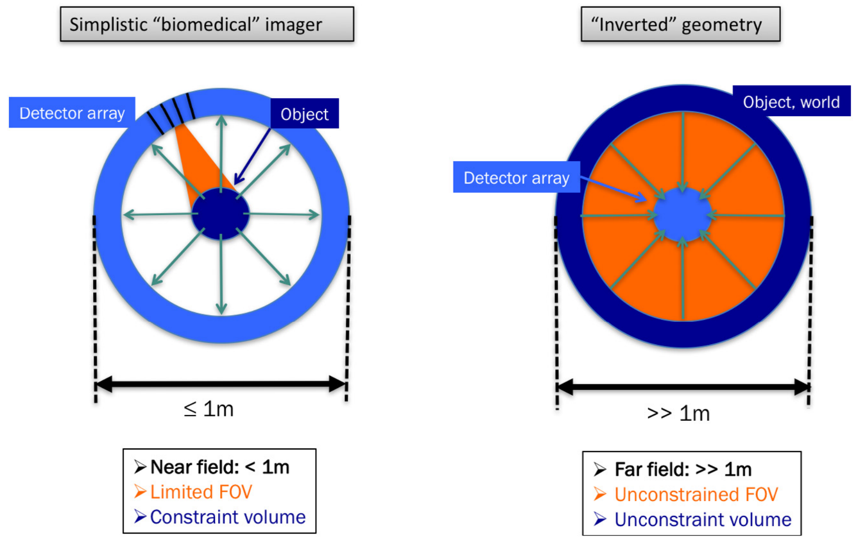

Fig. 1. Illustration of concepts and domains for gamma-ray imaging in "classical" biomedical imaging (left) and nuclear security and safety (right). Green arrows indicate the direction of gamma rays. In biomedical imaging, the object is restricted to a constrained FOV and the radiation source is restricted to a known and constrained volume that can be observed from many angles, always in a well-described geometry and path. In contrast, in nuclear security, the FOV and imaging volume can be unrestricted and only limited projections can be obtained. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

associated operations as well as the prevention of proliferation and illicit use of SNM internationally and domestically. The characteristic gamma-ray emission lines of these isotopes, and their decay daughters, serve as fingerprints to identify specific isotopes and their decay daughters. For applications related to radiological safety, gamma-ray imaging provides powerful means to detect and map leaks, lost sources, or contamination after nature- or man-induced accidents. Though in principle the objectives of gamma-ray imaging in the diverse fields mentioned above are similar, the contexts and domains are quite different, and require different implementations. Fig. 1 attempts to capture the main conceptual differences between medical imaging and imaging in nuclear security and safety. In biomedical imaging, the imaging object is well-constrained in space allowing a gamma-ray imager to be built around the object or to move in a well-defined path around the object such that the system may be designed to limit the field of view (FOV) for each detector to the imaged object. In nuclear security and safety or more broadly, in environmental imaging, the object is not necessarily constrained in space and the relationship between imaging system and image object are spatially inverted. In addition, since the measurements path is not fixed requiring a freely moving system, the location and orientation of the imaging instrument needs to be determined and tracked relative to the surrounding objects, or world.

Furthermore, the enormous gain in fusing different and complementary imaging modalities was recognized in medicine and biomedical imaging a long time ago, however, data fusion is not yet widely utilized in security and safety. For example, in medical, biomedical, or biological imaging, X-ray imaging is combined with gamma-ray imaging fusing anatomical and functional features in a high-dimensional image. In contrast, in the utilization of gamma-ray imaging for safety and security, to-date only static and two-dimensional gamma-ray image projections are overlaid with two-dimensional visual images, as indicated in Fig. 2 [1–14].

Recent advances in sensor technologies such as structured light or LiDAR now enable the full integration and fusion of "anatomical" or contextual and "functional" or gamma-ray imaging data in the less constrained security, safety, and environmental domain. In the following, we will briefly discuss the underlying concept of what we call scene-data fusion (SDF) followed by instruments we have successfully utilized to develop and demonstrate this concept. Results of measurements are split between ground-based and aerial deployments reflecting the wide range of applications for this new concept.

2. Scene-data fusion

The concept of scene-data fusion is based on the integration of contextual scene data with – in the broadest sense – any type of emission data in three dimensions [15–17]. The contextual scene data is obtained by sensors, such as visual cameras, structured light, or LiDAR that enable the reconstruction or mapping of a scene in 3-D. This scene or map is then used to determine the position and orientation (i.e. the pose) of the instrument in this scene, which is registering emissions from the scene constituents. We use Simultaneous Location and Mapping (SLAM) algorithms to achieve the mapping of the scene and tracking of the pose of the instrument [18]. SLAM is being used to create and update the scene map while simultaneously providing the six-dimensional information about location and orientation of the sensor within this scene map. It is widely being used in robotics tracking and navigation. The goal here is not to describe the details of the specific and publicly available SLAM algorithms, which we are employing but the fact that these algorithms can provide the critical information for the mapping, pose estimation, and ultimately the realization of 3-D SDF. In general, the output of the SLAM algorithm are point clouds representing the coordinates of object surfaces relative to the instrument.

While any emission data such as infrared or hyperspectral or radiation of nuclear origin such as gamma rays and neutrons can be used in SDF, our focus here is on gamma rays. Gamma rays provide powerful fingerprints for detecting and identifying specific radioisotopes, assuming the instrument is implemented as spectrometer, i.e. able to measure the energies of the gamma rays. The identification can be done for radioisotopes with known gamma-ray energies or the energies can be used to identify the radioisotope that is being observed.

Detecting the full energy of an incident gamma ray implies that the gamma ray did not scatter between the source and the detector and therefore, maintained the direction to the source. In addition, the number of counts in the full-energy or photo-peak can be associated with the amount or mass of the emitting source, assuming the absorbing material between source detector can be neglected, is known, or can be otherwise obtained. SDF does provide the information about the distance between the source and the detector at any moment of the measurement enabling the possibility to estimate of the source strength. The estimation of specific quantification is currently under development and not included here.