Nuclear Instruments and Methods in Physics Research A 800 (2015) 65–69

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Scene data fusion: Real-time standoff volumetric gamma-ray imaging

Ross Barnowski [a,*], Andrew Haefner [b], Lucian Mihailescu [b], Kai Vetter [a,b]

[a] Department of Nuclear Engineering, UC Berkeley, 4155 Etcheverry Hall, MC 1730, Berkeley, CA 94720, United States of America
[b] Lawrence Berkeley National Lab - Applied Nuclear Physics, 1 Cyclotron Road, Berkeley, CA 94720, United States of America

ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form
7 August 2015
Accepted 10 August 2015
Available online 15 August 2015

Keywords:
Compton imaging
Gamma-ray imaging
SLAM
3D imaging
Volumetric imaging
Data fusion

ABSTRACT

An approach to gamma-ray imaging has been developed that enables near real-time volumetric (3D) imaging of unknown environments thus improving the utility of gamma-ray imaging for source-search and radiation mapping applications. The approach, herein dubbed scene data fusion (SDF), is based on integrating mobile radiation imagers with real-time tracking and scene reconstruction algorithms to enable a mobile mode of operation and 3D localization of gamma-ray sources. A 3D model of the scene, provided in real-time by a simultaneous localization and mapping (SLAM) algorithm, is incorporated into the image reconstruction reducing the reconstruction time and improving imaging performance. The SDF concept is demonstrated in this work with a Microsoft Kinect RGB-D sensor, a real-time SLAM solver, and a cart-based Compton imaging platform comprised of two 3D position-sensitive high purity germanium (HPGe) detectors. An iterative algorithm based on Compton kinematics is used to reconstruct the gamma-ray source distribution in all three spatial dimensions. SDF advances the real-world applicability of gamma-ray imaging for many search, mapping, and verification scenarios by improving the tractiblity of the gamma-ray image reconstruction and providing context for the 3D localization of gamma-ray sources within the environment in real-time.

Published by Elsevier B.V.

1. Introduction

Gamma-ray imaging has many applications in a wide variety of fields, including gamma-ray astronomy, medical imaging, and nuclear security and safeguards. Additionally, the application of gamma-ray imaging to environmental monitoring and nuclear contamination remediation scenarios is being actively researched [1–3]. There exist several directional imaging methods that characterize the spatial distribution of gamma-ray sources in 2D. Compton and coded-aperture based methods have been used to provide sensitivity to the spatial distributions of cosmic gamma-ray sources [4,5], while collimator-based approaches have long been a staple in diagnostic imaging [6]. These methods have also been adopted for nuclear safeguards and security applications such as nuclear facility monitoring, source-search, and emergency response, as well as applications in nuclear contamination remediation. Many of these applications would further benefit from volumetric imaging; i.e. the ability to characterize gamma-ray source distributions in all three spatial dimensions, including depth. Previous work has investigated combining conventional 2D gamma-ray projection imaging techniques with 3D models of the scene [7]. This work demonstrates the value of the context provided by merging with 3D models, but falls short of data fusion as defined here because the 3D model information is not incorporated into the gamma-ray imaging technique. Reference [8] extends this work to true volumetric imaging via data fusion with the same set of data. Volumetric imaging is achieved in biomedical applications by leveraging the self-contained, near-field nature of the imaging domain. In some cases, this allows full or partial tomographic methods [9] to be applied for both transmission [10] and emission [11,12] based imaging modalities. There are other approaches that do not use tomographic reconstruction, but nevertheless rely on the self-contained nature of the imaging domain [13–15]. There are challenges unique to nuclear security and safeguards applications that preclude the direct application of these 3D methods: large variability of the size and complexity of the imaging environment; the inability to acquire orthogonal projections; and comparatively low count rates in real-world scenarios. Scene data fusion overcomes these challenges for standoff imaging, where “standoff” here represents distances in the range of one to tens of meters commensurate with the scale relevant for many nuclear security and safeguards applications.

The SDF approach is based on previous work [8] in which 3D models of the scene were incorporated into a volumetric gamma-ray image reconstruction algorithm. In that work, the detector had to be manually positioned and the models were laboriously constructed by hand using measurements taken with a laser range finder. Furthermore, thousands of Compton cones were used in the image

* Corresponding author.

http://dx.doi.org/10.1016/j.nima.2015.08.016
0168-9002/Published by Elsevier B.V.

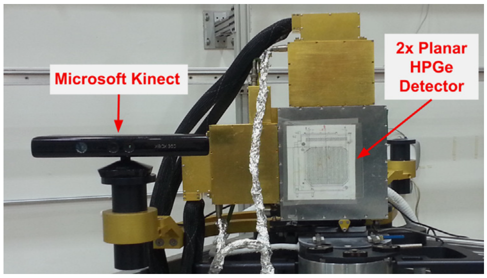

Fig. 1. The VCI system. The Kinect is mounted near the detector cryostat and kept stationary with respect to the detector. During volumetric measurements, the entire cart is pushed through the scene thus the detector and Kinect move together.

reconstruction. The SDF approach surmounts these limitations and enables a mobile mode of operation for portable radiation imaging devices. This is achieved by integrating a mobile radiation imaging platform with a real-time tracking method that provides an estimate of the location and orientation (i.e. pose) of the system as it moves throughout the scene. By synchronizing and spatially registering the pose estimates with the data from the radiation imager, a track throughout the scene populated with gamma-ray interactions is produced, serving as the input to a volumetric image reconstruction algorithm. In practice, these data alone often result in prohibitively noisy images due to the real-world imaging challenges detailed above. The 3D model of the scene can then be used to spatially constrain the gamma-ray image reconstruction, improving image quality in terms of localization accuracy and reduced image noise. SDF is defined by the utilization of both the localization and mapping capability provided by directly integrating SLAM-solvers and auxiliary sensors with radiation imaging systems, enabling a mobile imaging mode capable of 3D gamma-ray source localization. In principle, there are many ways by which the complementary data can be utilized in the reconstruction due to the multitude of imaging modalities (collimated, Compton) and the various approaches to the inversion (e.g. filtered back projection, iterative methods). This work focuses on a specific approach based on Compton imaging, which is particularly suited for source search and gamma-ray mapping applications due to the inherent wide field of view and sensitivity over a large range in gamma-ray energies [16].

2. System implementation – Volumetric Compton Imager

A mobile gamma-ray imager known as the Volumetric Compton Imager (VCI) served as the development platform for the SDF concept. The VCI is a cart-based mobile system consisting of two planar double-sided strip (DSS) HPGe detectors, as seen in Fig. 1. The two detectors are each 15.1 mm thick with 37 strip readouts per electrode with 2 mm pitch for a maximum sensitive detection volume of 82.6 cm^3 HPGe.[1] The detectors display the excellent energy resolution characteristic of HPGe, while the segmented readouts provide the position sensitivity necessary for Compton imaging [16].

The gamma-ray event reconstruction and tracking used in this work is not optimized for sensitivity as the focus of this work is real-time imaging. As a result, the position resolution and Compton imaging efficiency are limited, imposing an upper bound on the detection rate for imagable Compton events. Real-time imaging is demonstrated in Section 4 despite the artificially limited Compton event rate, illustrating the efficacy of SDF even for relatively inefficient gamma-ray imaging systems.

The SLAM-solver chosen for this work is known as RGBDSlam, and is presented in full detail in [17]. The system utilizes a Microsoft Kinect sensor that provides both RGB images and dense 3D point cloud representations of the environment at a frame rate $\geq$15 Hz and an effective range of 4–6 m depending on the configuration. The algorithm publishes estimates of the pose of the RGB-D sensor as well as an aggregate point cloud model of the scene in real time. The coordinate frame of the scene model is set by the first frame acquired from the Kinect, thus subsequent pose estimates represent a transformation from the current Kinect location to the scene coordinate frame. The RGB-D sensor is kept rigid with respect to the detectors on the VCI cart, and the relative transformation between the coordinate frame of the detector and the Kinect is determined. This registration transform is then applied to the Compton events collected by the detector to correctly orient them in the scene coordinate frame. By synchronizing the tracked pose of the detector with the Compton events, a full Compton event history along the track of the detector is compiled and updated in real time. The radiation image and the imaging space are continuously recomputed as new Compton events are measured along the detector track.

[1] In practice, issues with discrete electronics for several channels cause a slight reduction of the sensitive volume.

3. Volumetric image reconstruction algorithm

Given the ability to sample gamma-ray distributions with a mobile Compton imager, the challenge of determining the 3D spatial distribution of gamma-ray sources remains. Current far-field reconstruction methods developed for astronomy and nuclear security [18] based on filtered back-projection are not directly applicable to the 3D problem due to the higher dimensionality of the imaging space. Perhaps the greatest challenge is the arbitrary nature of the imaging environment itself; in general, it is unlikely that the imager will be able to obtain the orthogonal projections necessary for a full tomographic reconstruction. The reconstruction algorithm must also be able to handle the low count rates expected for real-world imaging applications. These considerations led to the development of an ML-EM reconstruction algorithm for far-field 3D Compton imaging with additional modifications to incorporate the complementary scene data.

3.1. ML-EM overview

A Poisson likelihood model is used to relate the gamma-ray source distribution to the data measured along the detector path. In the case of Compton imaging, the measured Compton cones describe from which voxels in the imaging space the gamma-rays could have originated. The EM portion of the algorithm maximizes the Poisson likelihood given this description of the imaging space [19]. List-mode reconstruction is used in this case, thus the sensitivities are not computed from the system matrix; uniform sensitivities are used instead. Furthermore, the system matrix is computed using a 3D cone with a Gaussian width, and voxels are assumed to be points in space. These simplifications facilitate real-time reconstruction, but are approximations that can result in imaging artifacts. However, it has been empirically determined that these simplifications are not prohibitive for localizing point sources in 3D.

3.2. Scene data constraint

As the 3D scene model is updated by RGBDSlam, the imaging space is recomputed based on the extent of the detector track within the model. The algorithm can use the scene model to compute an occupancy grid of the voxelized imaging space and limit the solution to the occupied voxels. This simple fusion technique is based on the assumption that gamma-ray sources are on the surface of or contained within objects and are not present in air or other void space.