Handheld Real-time Volumetric 3-D Gamma-ray Imaging

Andrew Haefner^a, Ross Barnowski^b, Paul Luke^a, Mark Amman^a, Kai Vetter^{b,a}

^a*Lawrence Berkeley National Lab - Applied Nuclear Physics, 1 Cyclotron Road, Berkeley CA, 94720, United States of America*

^b*Department of Nuclear Engineering, UC Berkeley, 4155 Etcheverry Hall, MC 1730, Berkeley CA 94720, United States of America*

Abstract

This paper presents the concept of real-time fusion of gamma-ray imaging and visual scene data for a hand-held mobile Compton imaging system in 3-D. The ability to obtain and integrate both gamma-ray and scene data from a mobile platform enables improved capabilities in the localization and mapping of radioactive materials. This not only enhances the ability to localize these materials, it provides important contextual information of the scene, which once acquired, can be reviewed and further analyzed subsequently. To demonstrate these concepts, the High-Efficiency Multimode Imager (HEMI) is used in a hand-portable implementation in combination with a Microsoft Kinect sensor. This sensor, in conjunction with open-source software, provides the ability to create a 3-D model of the scene and to track the position and orientation of HEMI in real-time. By combining the gamma-ray data and visual data, accurate 3-D maps of gamma-ray sources are produced in real-time. This approach is extended to map the location of radioactive materials within objects with unknown geometry.

Keywords: Compton imaging, Gamma-ray imaging, SLAM, 3-D Imaging, Volumetric Imaging, Data Fusion

1. Introduction and Background

Detecting, localizing, and mapping gamma-ray emitting objects in real-world environments are important capabilities for many applications including nuclear security and safety, emergency response, consequence management, and nuclear contamination remediation. Currently, static or portable non-imaging detectors and in some cases, static gamma-ray imaging instruments are employed, depending on the specific requirements. Combining hand-portable gamma-ray imaging systems with contextual sensors such as cameras or depth sensors enables the reconstruction of a scene with the embedded gamma-ray emission distribution in three dimensions in real-time. The ability to localize radioactive materials in arbitrary environments in three dimensions provides important additional details about their spatial distribution, including contextual information; for example, the relation of the materials (inside or outside) to other objects in the scene. Since the scene with integrated gamma-ray image information, the path of the system through the scene, and the associated time evolution can be stored digitally, all the information can be re-analyzed after the measurement is complete. In this way, the measurement can be replayed and other clues and features can be studied. Scene-data fusion can also provide more sophisticated capabilities in areas with limited or no access, such as inside of shipping containers, providing new means of localizing and characterizing radioactive materials within such containers. This method also improves capabilities for search scenarios by helping to mitigate the geometric inverse distance square intensity reduction as the portable imager can be brought closer to the detected emission source. The ability to move freely throughout a scene and to observe multiple perspectives of an object can further aid in the detection and characterization of sources and associated shielding. Additionally, the three-dimensional (3D) scene model can be used to constrain the position of gamma-ray emitting objects, potentially reducing computational time and improving accuracy of the source reconstruction.

Static and two-dimensional gamma-ray imaging in combination with two-

31 dimensional overlays on visual images is available commercially [1][2], and has
 32 been demonstrated in relevant environments, such as contaminated areas in
 33 Fukushima Prefecture, Japan [3]. Near-field 3-D gamma-ray imaging on the or-
 34 der of millimeters has been demonstrated with a handheld Compton camera [4].
 35 In larger areas, 3-D gamma-ray imaging was demonstrated with a coded aper-
 36 ture system combined with a LIDAR scan using a static measurement [5], which
 37 is limited due to the single perspective. Volumetric 3-D imaging was demon-
 38 strated in offline processing with multiple perspectives combined with a LIDAR
 39 scan and Compton imaging [6]. More recently, the concept of real-time volu-
 40 metric imaging and scene data fusion was demonstrated employing a cart-based
 41 Compton imaging instrument consisting of three-dimensional position sensitive
 42 HPGe detectors paired with a Microsoft Kinect system [7]. In that configura-
 43 tion, the size and weight of the cart limited the types of measurements that
 44 were possible. Nevertheless, real-time 3-D scene data fusion was successfully
 45 demonstrated with that system. This paper presents an implementation of real-
 46 time 3D scene data fusion on a hand-portable instrument and demonstrates the
 47 effective localization of a range of gamma-ray sources around or within objects.
 48 Several of the measurements shown would not be possible from the cart based
 49 system.

50 Our approach in this paper is to perform near real-time (i.e. within seconds)
 51 3-D gamma-ray reconstruction of scenes from a handheld system. As the system
 52 collects data, a 3-D estimate of the source distribution is created and updated
 53 as more data are collected. This paper introduces the measurement system,
 54 the data processing approach and demonstrates a variety of capabilities with
 55 relevant lab measurements. The lab measurements begin with single sources
 56 on open surfaces to convey the 3-D and real-time nature of the reconstruction.
 57 A second measurement serves to demonstrate the difference with conventional
 58 static 2-D imaging. Then the simultaneous measurement of multiple source
 59 energies and locations is shown. Finally, measurements of sources within objects
 60 are shown to demonstrate localization for passive object interrogation scenarios.
 61 While this paper focuses on our specific handheld implementation, the mobile 3D

62 scene-data fusion concept can also be integrated with autonomous platforms on
 63 land or in the air. This has been demonstrated with the system used in this work
 64 in combination with contextual visual cameras on an Unmanned Aerial System
 65 (UAS) in the Fukushima Prefecture already [8]. In general, the advantage of such
 66 a system is the ability to deploy into areas with limited access or where the risk
 67 to human operators is too high. The advantage of the 3-D approach is to better
 68 account for the 3-D geometry of the scene. UAS deployments also enhance the
 69 effectiveness in the mapping of radioactive contamination [9]. The concept of
 70 3-D scene data fusion can easily be extended to the detection and mapping of
 71 neutrons or other radiation, including imaging or non-imaging modalities.

72 **2. High Efficiency Multimode Imager and System**

73 The detector used for this work is the High Efficiency Multimode Imager
 74 (HEMI). The HEMI design consists of 96, 1 cm³ CdZnTe (CZT) crystals, each
 75 with a coplanar grid (CPG) readout, arranged in a 2-plane active-mask con-
 76 figuration with the front plane half populated in a random mask pattern (32
 77 detector elements) and the back-plane fully populated (64 detector elements)
 78 [10] [11]. The active mask configuration was selected to allow the simultaneous
 79 use of coded aperture and Compton imaging modalities. This work focuses on
 80 HEMI's Compton imaging capability. The use of CZT detectors operated at
 81 room-temperature with CPG readout and active coded-mask provides simple
 82 operation with an excellent performance-to-weight ratio. The total mass of the
 83 instrument including batteries for HEMI is about 3.6 kg. The battery life for
 84 HEMI is about 5 hours, with the battery life of the laptop and tablet of several
 85 hours remaining the limiting factor for mobile measurements. HEMI is charac-
 86 terized by a relative energy resolution of 2.5% FWHM and an angular resolution
 87 of about 10° FWHM at 662 keV [12]. One benefit of this free moving approach
 88 is that moving HEMI close to objects serves to mitigate its coarse angular res-
 89 olution because the spatial resolution depends on the distance to objects. This
 90 point is explored more in Section 4.1.

91 HEMI is combined with the Microsoft Kinect sensor in a hand-portable
implementation in this work as illustrated in Fig. 1. All of the associated com-

Figure 1: Hand-portable operation of the integrated HEMI and Kinect system. The user carries the device around the scene and receives actionable gamma-ray imaging feedback in real-time on the tablet.

92
93 puters for collecting data with HEMI are shown in Fig. 2 and include: a tablet
94 for instrument control and data visualization, and a laptop that performs the
95 visual data processing as shown in Fig. 2. The Kinect provides both RGB
96 images and dense point cloud representation of the scene within its field-of-view
97 of 43° vertical and 57° horizontal at up to 30 Hz frame rate. Using Simulta-
98 neous Localization and Mapping (SLAM) performed on the laptop, the visual
99 and geometric data from the Kinect is processed to create a 3-D model of the
100 environment and simultaneously track the device position and orientation in
101 real-time. This work utilizes the RGBD-SLAM algorithm [13], which relies on
102 the visual RGB information along with the depth information from the Kinect.

103 The visual reconstruction performed on the laptop utilizes a GPU to operate
104 in real-time. The fusion of the gamma-ray image and visual data is performed
105 on the tablet and is less computationally intensive compared to the SLAM
106 component. The tablet is a Microsoft Surface 3, with 8 GB of RAM and a
107 dual core i7 Intel processor. This is sufficient for real-time 3-D data fusion,
108 which includes the combination of the 3-D visual model and the gamma-ray

Figure 2: HEMI with Kinect and the computers used for real-time processing of data.

109 Compton imaging events, in areas the size of a single room. The computed
 110 visual model and detector locations are sent wirelessly to the tablet where the
 111 data are integrated with the gamma-ray data. Real-time feedback is displayed
 112 on the tablet as the data are collected and processed.

113 3. Reconstruction Approach

114 Compton imaging requires the reconstruction of the gamma-ray interaction
 115 positions within the detector array. The positions of the first two interactions
 116 define the symmetry axis of a cone whose opening angle is defined by the energy
 117 deposited in the first interaction and the energy of the incident gamma ray. The
 118 cone represents all possible incident directions for the specific gamma ray. The
 119 accumulation of multiple cones, each determined from an independent interac-
 120 tion sequence, is necessary to reconstruct the gamma-ray source distribution. In
 121 HEMI, the locations and energies of the gamma-ray interactions are determined
 122 by the positions of and measured energy in each of the CZT detector elements.
 123 Typically, an interaction sequence involving two elements is required, and the
 124 sum energy is assumed to be the incident gamma-ray energy. In this analysis,

125 both possible scattering sequences from each pair of interactions are used in
 126 the gamma-ray image reconstruction. This decision is based on the assumption
 127 that given the low number of counts, losses of potential Compton cones due
 128 to mis-sequencing should be minimized. As an additional requirement in the
 129 Compton event reconstruction, a lever arm cut of 2.1 cm is applied, where the
 130 lever arm is computed as the distance from the center of each detector element
 131 in which that event occurred. This was used to remove events involving adjacent
 132 or diagonal detector elements. These events have very poor angular resolution
 133 due to the size and proximity of the detectors. The cone width is set to 10°
 134 FWHM, reflecting the expected angular uncertainty of the HEMI system.

135 For the gamma-ray image reconstruction, a list mode maximum likelihood
 136 expectation maximization (LM-ML-EM) method was used [14]. Compton imag-
 137 ing often requires list-mode operation due to the high number of dimensions
 138 across the data space, which can include 3-D interaction positions and energies,
 139 and location and orientation of the detector, etc. ML-EM is known to have
 140 convergence issues for distributed sources [15] (for example, different image fre-
 141 quencies converge at different rates), but this work focuses on point or compact
 142 sources relevant for many search applications. There are three main compu-
 143 tational components associated with ML-EM: computing the system matrix,
 144 computing sensitivity, and computing the iterations. Sensitivity is assumed to
 145 be uniform, which is reasonable for the point source scenarios investigated in this
 146 work. Distributed sources would require a more detailed sensitivity calculation.

147 One additional challenge with reconstructing arbitrary environments is the
 148 handling of cones that do not fully intersect the available imaging area. For
 149 example, a cone that only intersects one voxel on the edge of the image space
 150 can amplify noise in that voxel through the image reconstruction. To overcome
 151 the bias induced by cones or portions of cones outside of the imaging area, cones
 152 that intersect with less than 10% of the image space are removed. As the image
 153 space and the number of events increase during the dynamic measurement, the
 154 reconstruction speed decreases. In general search scenarios, the increase in the
 155 imaging space drives the reduction of the reconstruction speed, while in the

mapping of highly contaminated areas, the number of recorded events drive the reduction in reconstruction speed. Thus, the approach presented here is limited in spatial size and number of counts.

Computationally, the gamma-ray image reconstruction runs on its own processing thread and uses the system location and 3-D model from SLAM along with the gamma-ray data as inputs. The 3-D reconstruction returns results as it finishes processing and then recomputes the reconstruction. Thus its computation time span depends on the number of events and size of the model space.

4. Results

In the following section, the results of several measurements employing real-time 3D scene data fusion on a hand-portable gamma-ray imaging system are presented. Measurements of several source configurations with a range of source energies around and within objects are included.

4.1. Single Source and 2-D Comparison

In a lab environment, a Cs-137 source with an activity of 40 μCi is placed in the scene. The hand-portable HEMI was moved through the lab and the scene and the location of the source were reconstructed as the measurement progressed. Fig. 3 and Fig. 4 illustrates the concept of real-time scene and integrated gamma-ray image reconstruction by showing snapshots of the reconstruction and a visual image of where the detector and operator are in the scene.

The red line indicates the path of the instrument in the scene and the white dots indicate the locations of Compton events that were used for the gamma-ray reconstruction. The blue arrows indicate the scattering directions of the gamma rays for Compton events in the detector. The accuracy of the gamma-ray reconstruction is on the order of the voxel size of 10 cm. This size is chosen to ensure the number of voxels does not get too large for the rooms measured in this paper. The measurement time was less than one minute. Some pixelization noise around the source is observed, which may result from the uncertainty

Figure 3: The evolution of the real-time reconstruction at 16 second intervals. The estimation for the Cs-137 source location improves as more data is collected. The blue arrows are the Compton events used in the reconstruction, the line is the path of the detector in the scene and the white circles are the location of the cone vertex. The details of the reconstruction are challenging to see in this figure, but it is shown to convey the fact that the result updates sequentially as more data is collected.

Figure 4: This shows the final reconstruction from walking around in a lab scene. The estimation for the Cs-137 source location improves as more data is collected. The blue arrows are the Compton events used in the reconstruction, the line is the path of the detector in the scene and the white circles are the location of the cone vertex.

185 in the cone opening angle not reflecting the actual uncertainty inherent in the
 186 Compton cone. Subsequent measurements with a parameter for cone opening
 187 angle that better matches the angular resolution of the system (10 degrees) show
 188 a reduction in image noise, possibly as a result of a more realistic intersection
 189 of the probability surface with the voxels of the image space. In addition to the
 190 ability to reconstruct the location of a source in 3D with few events, the real-
 191 time feedback has the advantage of guiding the user and verifying the proper
 192 operation of the instrument and the reconstruction. For example, if the scene
 193 reconstruction or the tracking is lost, the user would quickly notice and can take
 194 appropriate action to return to a previous position and recover tracking.

195 In order to compare the 3-D method with conventional static 2-D imaging,
 196 HEMI is used as a static imager to reconstruct the 2-D projection of the gamma
 197 rays. For this measurement, HEMI was placed in the center of the walking path
 198 used to create the 3-D reconstruction with the source in the same position, which
 199 puts HEMI 2.6 m from the source. At this distance, the spatial resolution at the
 200 sources is about 0.45 m FWHM given HEMI's angular resolution of 10 degrees
 201 FWHM. When HEMI is about 1 m away from the source, as is the case when
 202 walking around the room, the resolution is about 0.17 m FWHM. The given
 203 spatial resolution values are specific to this scenario, but it is important to note
 204 how the spatial resolution can be improved in the 3-D approach compared to
 205 the static 2-D approach. Fig. 5a shows the 2-D image that is created after 1 min
 206 measurement time, which is about the length of time for the 3-D measurement.
 207 The reconstruction method used is a real-time filtered back-projection (FBP)
 208 described in [16]. The result after one minute is noisy and inaccurate, with the
 209 hotspot off from the true location by several degrees. The image noise results
 210 from the low count rate and the fact that FBP does not include a proper Poisson
 211 noise model. The reconstructed image improves after further measurement time,
 212 as shown in Fig. 5b and the reconstructed source location is more accurate.
 213 This shows that, conceptually, the static 2-D approach provides less accurate
 214 information about the source location in a longer time. This is largely due to
 215 the inverse square of the distance fall off of the signal, a fundamental limit in

Figure 5: This shows a conventional representation of static 2-D Compton images of the Cs-137 source with a visual overlay of the lab scene.

the static mode and possibly that the 3-D solution is constrained to the visual point cloud. Walking around the scene also helps improve spatial resolution when the detector moves closer to sources.

4.2. Reconstruction of Multiple Sources

One of the important features of scene data fusion from handheld HEMI is the ability to reconstruct gamma-ray images from a range of radioisotopes, each with different characteristic gamma-ray energies. To demonstrate this, three sources were placed on top of objects in a lab scene: Na-22, Cs-137 and Mn-54 with activities of 10 μCi , 8 μCi , and 5 μCi , respectively. Fig. 6 shows the coincidence energy spectrum obtained during a measurement, which is obtained by summing the energies from two interactions from a time coincident event. The coincidence time used was 1.2 μs and was the same for all measurements in this work. All three sources can easily be identified in the spectra: Na-22 with energies of 511 keV and 1275 keV, Cs-137 with 662 keV, and Mn-54 with 835 keV. Fig. 7 shows the reconstructed sources in the 3D scene obtained with energy gates set on 511 keV (red), 662 keV (green), and 835 keV (blue) with a gate width of 20 keV. For each of these energies the source distribution was reconstructed over the entire volume encompassed by the visual data. All three sources were correctly localized within one voxel of the true source location.

Figure 6: The coincident event energy spectra from a run with three sources, Na-22, Cs-137, and Mn-54. The total measurement time was 177 sec.

235 There is some broadening in the location of the source by several voxels, likely
 236 due to error in the tracking, which is illustrated by the variation in the white line
 237 that represents the path of the detector in the scene. This is due to accumulation
 238 of errors along the track and can be improved in future work.

239 Table 1 shows the parameters used in the measurement and reconstruction.
 240 The measurement time was less than 3 minutes. In this example, the imaging
 241 space is reduced by about a factor of 50 due to the constraints to the surfaces of
 242 the objects in the reconstructed scene. Table 2 shows some reconstruction time
 243 parameters, including the time to compute the system matrix for all the data
 244 and the time for 10 ML-EM iterations for the difference energy sources. This
 245 also shows the number of cones used in the reconstruction.

246 A second set of measurements was performed to illustrate the ability to
 247 integrate scene and gamma-ray image data for multiple sources contained in
 248 different containers or in cabinets. Ba-133, Na-22, and Cs-137 sources were
 249 hidden in a cupboard, a source safe, and a toolbox on top of a bench, respec-

(a)

(b)

(c)

Figure 7: Figure (a) shows the 3-D colorized scene without the gamma-ray reconstruction. The white line reflects the path of the instrument in the scene. Figure (b) shows a side view of the scene with the reconstructed 3-D locations of three different gamma-ray source locations. In this figure the 3-D point cloud is plotted in black and white to allow better contrast with the colored gamma-ray reconstructions. Figure (c) shows a top view of the scene with three sources visible.

Parameter	Value
Voxel size	10 cm
Voxel Dimensions	148 x 226 x 98
Number of Iterations	10
Measurement Time	177 sec
Total Voxels	3,277,904
Restricted Voxels	62,714
Percent Filled	1.9%

Table 1: These are some parameters from the single source measurement. The voxel size represents the extension of a voxel in the image space. The voxel dimension represents the overall imaging space. The number of iterations refers to the iterative maximum-likelihood gamma-ray reconstruction. The restricted number of voxels refers to the number of voxels actually being used based on the scene reconstruction.

Energy (keV)	Cones	System Matrix (ms)	10 Iterations (ms)
511	233	924	112
662	123	470	65
834	67	266	37

Table 2: This table shows some reconstruction time parameters for the three different sources shown in this section.

tively, as shown in Fig. 8. The measurement time was about 100 seconds. The coincidence energy spectrum obtained in one measurement is shown in Fig. 9.

The energies at 511 keV and 1275 keV from Na-22 and the energy of 662 keV from Cs-137 are clearly visible, while the strongest line of Ba-133 line at 356 keV has a poor signal-to-background and is barely visible. In spite of this, all three sources are localized. Fig. 8 shows the reconstructed scene and the fused gamma-ray image of the three source locations. In this reconstruction each color is a different energy as follows: red for 356 keV, green for 511 keV and blue for 662 keV corresponding to Ba-133, Na-22 and Cs-137 respectively. Some image noise is observed in the reconstruction of the photons at 356 keV and 511 keV, which could be due to higher energy gamma-rays that are down-scattered into the detector or partial deposition escape events. It is interesting to note that the Ba-133 source is correctly localized even though the 356 keV peak is not very prominent in the coincidence spectrum. The Cs-137 source inside the safe was localized slightly above the position inside the top of the safe. This could be due to restricting the reconstruction to the point cloud.

4.3. Source Within an Object

Scene data fusion with a handheld imager can also be used to position sources inside objects that are not accessible. To demonstrate this, a 30 μ Ci Cs-137 source was placed slightly off center inside of a cardboard box. Fig. 10 illustrates the ability to use the dynamic 3D imaging method to detect and localize sources inside of objects. The white lines are the tracked location of HEMI as it was moved in the scene. The red hotspot is the reconstructed source location that was obtained within a 50 second measurement time. In this reconstruction, the source was not restricted to the surface of the box. This increases the reconstruction time as the entire space around the track is voxelized to perform the reconstruction. In contrast to the previous examples, in this scenario it was possible to walk around the object of interest, thereby providing a more complete set of projections and making it reasonable to voxelize the entire space.

(a)

(b)

(c)

Figure 8: Figure (a) shows the 3-D colored scene without the gamma-ray reconstruction. Figure (b) shows the three localized sources identified by their energies of 356 keV (red), 511 keV (green) and 662 keV (blue) respectively. Figure (c) shows a top down view of the data shown in (b). The white line represents the path of the instrument relative to the scene. The colored dots on the path reflect gamma-ray events used in their respective image reconstruction.

Figure 9: Coincidence energy spectrum from Ba-133, Na-22, and Cs-137 sources, placed in and around a lab bench as shown in Fig. 8. The 511 keV and 1275 keV lines of Na-22 and the 662 keV line of Cs-137 are clearly visible. In contrast, the strongest line at 356 keV of Ba-133 is barely visible in the spectrum. The total measurement time was about 100 seconds.

(a)

(b)

(c)

Figure 10: Reconstruction of a Cs-137 source inside of a box. The white line represents the path taken in the scene. The gamma-ray reconstruction was not constrained to any object.

279 5. Conclusion

280 This paper demonstrates real-time fusion of gamma-ray image and visual
281 scene data with a hand-held and mobile Compton imaging system. Due to the
282 movement of the system, several projections are obtained enabling the 3-D re-
283 construction of gamma-ray sources while at the same time increasing the speed
284 and dimensionality of localization due to mitigating the $1/r^2$ intensity reduc-
285 tion. Measurements of sources placed openly in a lab and inside of a container
286 were performed and localization was accomplished within several minutes for
287 all cases, with sources on the order of $10\ \mu\text{Ci}$. 3-D localization is successfully
288 demonstrated in room-sized lab environments, but further work is needed to
289 extend this approach to larger scales while maintaining the 10 cm localization.
290 While the Kinect is an affordable contextual sensor that can be integrated into
291 the data acquisition and processing framework easily to provide real-time capa-
292 bilities, it is limited to indoor scenarios due to its dependence on active infrared-
293 light. However, visual cameras can be used to create 3-D models indoors and
294 outdoors [17]. It is noteworthy that the mobile and real-time scene-data fusion
295 concept is not restricted to portable gamma-ray imaging systems but can also
296 be coupled with non-imaging counting or spectroscopic detectors. In addition, it
297 can be extended to other modalities and radiation types, including, for example,
298 the detection or imaging of neutrons.

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