Investigation of Combined Measurements with Three-Dimensional Design Information Verification System and Gamma-Ray Imaging Systems for International Safeguards Applications

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Abstract

A technical collaborative effort has been established to investigate the use of a three-dimensional (3D) laser imaging system combined with gamma-ray imaging systems for international safeguards applications. The effort is being conducted by Oak Ridge National Laboratory (ORNL), Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), the Joint Research Centre at Ispra, Italy (JRC-Ispra), and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) in the framework of the technical cooperation agreements between the U.S. Department of Energy (DOE) and the European Atomic Energy Commission and between DOE and ABACC.

Being able to verify declared technical design information of nuclear facilities is an important aspect of every safeguards approach. In addition to visual observation, it is relevant to know if nuclear material is present or has been present in piping and ducts not declared. In a previous study, ORNL, LLNL and JRC-Ispra demonstrated the capability of combining outputs from a commercially available 3D laser system and gamma-ray imager prototypes. The possibility of combining different measurement techniques into one tool will optimize the inspection effort and increase safeguards effectiveness.

This paper describes the collaborative effort; presents the technologies under investigation, Compton imaging and coded aperture gamma-imager prototypes, and the 3D laser imager; and introduces the preliminary results of measurements conducted in controlled environments.

Introduction

The submission of nuclear facility design information and the verification of this information usually occur during the earliest stages of construction, and the information is periodically re-verified over the operating life of the facility. The design information is verified during construction to define and include the nuclear material processing areas. Regional and international safeguards inspectors continue to re-verify the design information during what are called design information verification (DIV) activities conducted over the life of the plant, from construction through commissioning, operation, and shutdown to decommissioning.

From a safeguards perspective, being able to verify declared technical design information of nuclear facilities is an important aspect of every safeguards approach. In addition to visual observation, it is relevant to know if undeclared nuclear material is present or has been present in equipment piping and ducts. The possibility of combining different measurement techniques into one tool will optimize the inspection effort and increase safeguards effectiveness. The system under investigation will allow the identification of changes in piping configurations, as well as locate radioactive material where it is not supposed to be, for example in a declared cooling pipe that holds radioactive material.

Currently, the standard routine for performing nondestructive assay measurements is to use scintillator or solid-state gamma-ray detectors to look for the gamma signature given off by uranium isotopes. Several limitations are encountered with this practice: (1) uranium deposits are sometimes located behind heavy processing equipment, hindering physical access to the source of radiation; (2) an adequate survey of a radiation area requires considerable manpower and time; and (3) radiation detectors are omnidirectional in that they do not provide information related to the direction of incident radiation.

The idea of combining three-dimensional (3D) laser maps with radiometric images arose out of a collaboration project among the Joint Research Centre at Ispra, Italy (JRC-Ispra), Oak Ridge National Laboratory (ORNL), and Lawrence Livermore National Laboratory (LLNL). ORNL researchers had obtained a 3D laser system from JRC-Ispra, which they then transported to LLNL for investigation of the possibility of back-projecting its 3D maps onto images obtained from a Compton-based imager. As expected, the combined image enabled them to simultaneously examine radiometric information and pipe configuration. Building upon the work done at LLNL, ORNL investigated the performance of pinhole and coded-aperture gamma-ray imaging systems. With the aid of JRC-Ispra, gamma-ray images and 3D maps will be combined. The concept has been proven, and a field test will be conducted in an operating radiological facility safeguarded by the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC).

Background

ORNL, LLNL, and JRC-Ispra have demonstrated the capability of combining outputs from the 3D laser system and the gamma-ray imager prototypes for potential safeguards applications.

JRC-Ispra has developed a 3D laser scanning system (Figs. 1 and 2) for DIV that is currently being used by the International Atomic Energy Agency (IAEA). The system is able to create 3D maps of rooms and objects and to identify changes in positions and modifications with a precision on the order of millimeters. The 3D-DIV system was made available to ORNL by JRC-Ispra under a collaborative project concerning investigation of applications for the 3D-DIV system at U.S. Department of Energy (DOE) facilities in the United States. ORNL tested and evaluated the system and documented the procedures for use, hazard analyses, and identification of additional safeguards applications in a technical joint report [1].

Figure 1. Portable 3D laser scanning system. Unit used in 2006 and 2008 to conduct preliminary tests in laboratory.

Figure 2. New model of 3D laser that will be used to complete the project. Battery is now part of the single unit, which also stores the image.

The latest gamma-ray imaging system prototype developed by LLNL, and currently located at Lawrence Berkeley National Laboratory (LBNL), consists of a 4π field-of-view Compton imaging system (Fig. 3) with four double-sided segment detector (DSSD): two high-purity germanium (Ge) and two lithium drifted silicon detectors placed in two cryostats (Fig. 4). The Compton imaging instrument not only provides imaging capabilities, but provides excellent energy resolution which enables the identification of radioisotopes and nuclear materials.

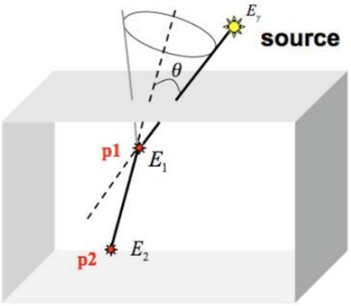

Figure 3. A conic imaging element derived from an interaction sequence of two energy DSSD Ge detector depositions (E1, E2) at p1 and p2 from an incident gamma-ray source with energy Eγ [2].

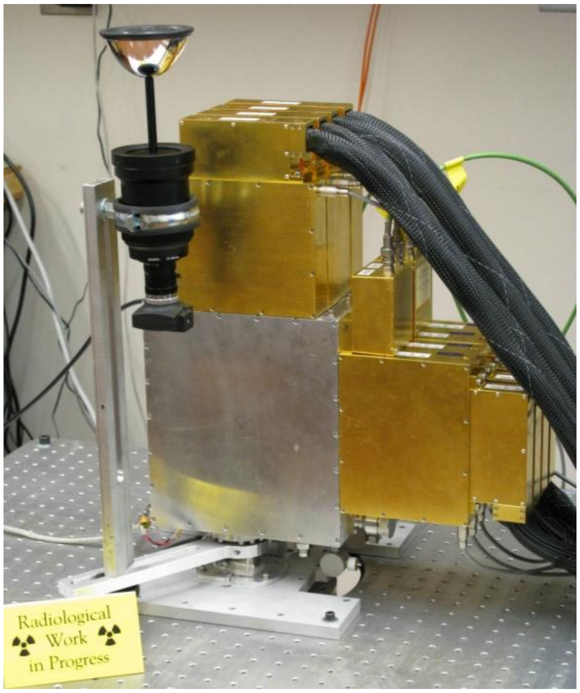

Figure 4. The Compact Compton Imager (CCI-2) prototype.

JRC-Ispra successfully merged LLNL's gamma-ray images obtained with a previous imaging prototype (CCI-1) with the 3D range maps obtained by ORNL under the above-mentioned collaboration project (Fig. 5) [3]. The results of these measurements were presented to the IAEA as a potential tool for safeguards inspections. The parties involved are taking the project to the next phase by testing the combined 3D laser scanner and gamma-ray imaging systems in a real facility. A future phase will include investigating the feasibility of combining 3D laser and neutron imaging technology.

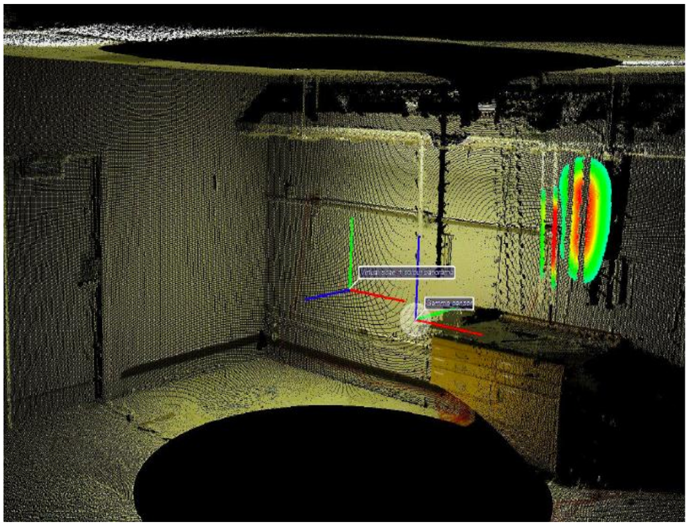

Figure 5. Compton image back-projected onto a 3D-DIV map.

ORNL has a Ge-based, coded aperture gamma-imager prototype (Figs. 6 and 7) originally developed jointly by LLNL and LBNL [4-5]. It employs a 38 × 38 cross-strip planar Ge detector 11 mm thick with a 2 mm pitch. A 5 cm thick, 8 cm diameter coaxial Ge detector is implemented to increase the detection efficiency of higher energy gamma rays. The coded aperture is a 6.1 mm thick mask made of tungsten. Preliminary tests conducted at ORNL showed that the coded aperture instrument provided a comprehensive radiometric image and also correctly predicted the geometric distribution of the source.

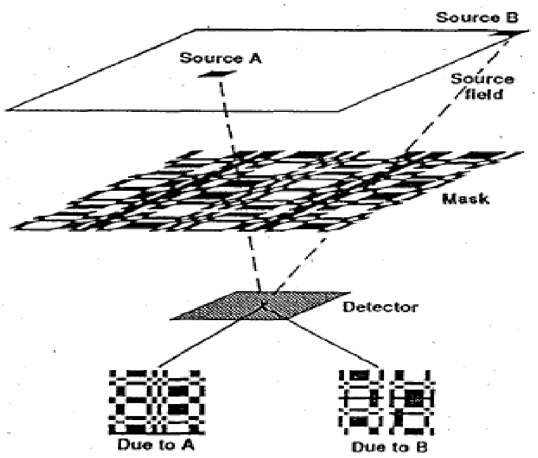

Figure 6. Images produced with coded apertures arise out of source pixels from a source field casting unique shadows onto the detector [5].

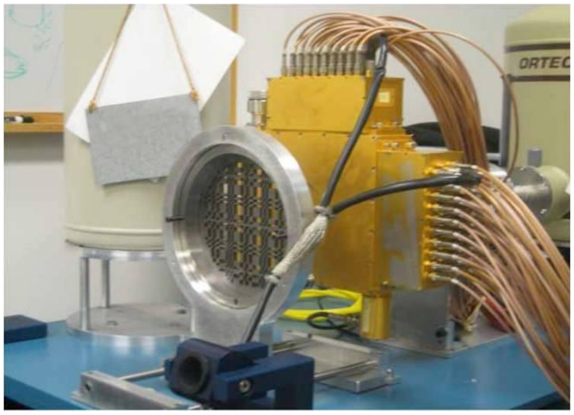

Figure 7. Coded aperture imager. Both the planar and coax detectors are cooled by liquid nitrogen. The coax detector was not used for image acquisition.

Scope of Work

The scope of work for this project is as follows:

1. ORNL will investigate and document efficiency of commercially available gamma-ray imaging systems and potential applicability for use with 3D-DIV system, or as a standalone system, for international safeguards.
2. LLNL and LBNL will conduct laboratory tests with the Compton gamma-ray imaging system prototype to assess its performance. Also, integration of a mobile platform for the gamma imaging will be performed so that the whole system can have more maneuverability.
3. ORNL, LLNL, and LBNL will conduct integrated system laboratory experiments.
4. Technical visit will be taken to operating facility in South America. Technical representatives from each participating laboratory made a trip to Argentina to visit a facility safeguarded by ABACC. The visit allowed the principle investigators to learn more about the problems and conditions under which the instrumentation will be used.
5. ORNL will acquire a 3D laser scanner to conduct simultaneous measurements with gamma imagers
6. Each participating laboratory will conduct sets of measurements (Fig. 8) to adjust the technologies to the environment and needs found during the visit to the operating facility at which field tests will take place.
7. JRC-Ispra will combine the sets of images collected with the 3D laser and gamma imagers during measurement campaign.
8. Results of measurement campaign will be shared and analyzed jointly by all parties.
9. Participating DOE laboratories and JRC-Ispra will provide demonstration and training for ABACC representatives on technologies.
10. DOE laboratories will make any final adjustments to their technologies to participate in field test.
11. All parties will participate in field test in facility safeguarded by ABACC in South America.
12. All parties will document findings of experiments and share results with the IAEA.

Figure 8: A shut down 0.5 MT/day demonstration facility in Oak Ridge where measurement campaign will be conducted.

Results of Preliminary Laboratory Tests

Measurements were performed at the ORNL Safeguards Laboratory using sources that model holdup in radiological facilities. They showed that for situations with moderate amounts of solid or dense uranium sources, the coded aperture was able to predict source location and geometry within ~7% of actual values, while the pinhole gave a broad representation of source distributions (Fig. 9).

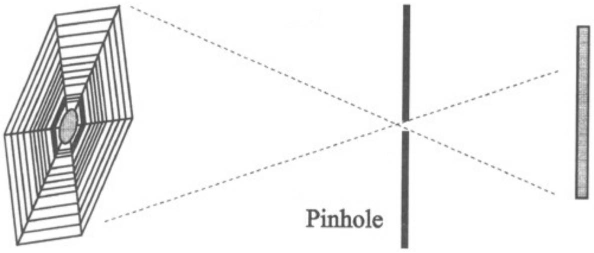

Figure 9. Schematic showing the mechanism of pinhole imaging. Because no lens is used, the final image will be upside down relative to the imaged object [6].

Figure 10. RadScan imaging device (Pajarito Scientific Corporation) [7].

Pajarito Scientific Corporation kindly supplied the pinhole-imaging device, RadScan, used at ORNL during the summer of 2008 (Figure 10). It consists of a sodium iodide scintillation detector positioned behind a tungsten collimator. The detector is not pixilated, which means that the instrument must raster scan an area of interest for image acquisition. Attached to the imaging head is a digital camera, which is used to overlay radiometric data with scanned area photographs. The imaging head can either hang freely or be mounted on a tripod, depending on the measurement conditions.

Results from the preliminary test are shown in Fig. 11. The coded aperture instrument provided a comprehensive radiometric image, as evinced by the clear presence of the U_3O_8 line sources. It also correctly identified the geometric distribution of the sources. With image pixels corresponding to ~7 cm in the experimental geometry, the lengths of the line sources were computed to be ~85 cm. The distance between the top and center UF_4 vials was calculated to be ~49 cm, while the distance between the center and bottom vials was ~42 cm. The RadScan detected UF_4 vials at the pipe array hinges but gave a broad representation of the line sources. This result is attributed to its non-pixilated detector setup; with a 2.5 h integration, the RadScan has a dwell time of 2 min for each position on the pipe array. Thus, for distributed sources modeling nuclear holdup, using the coded aperture instrument is preferable.

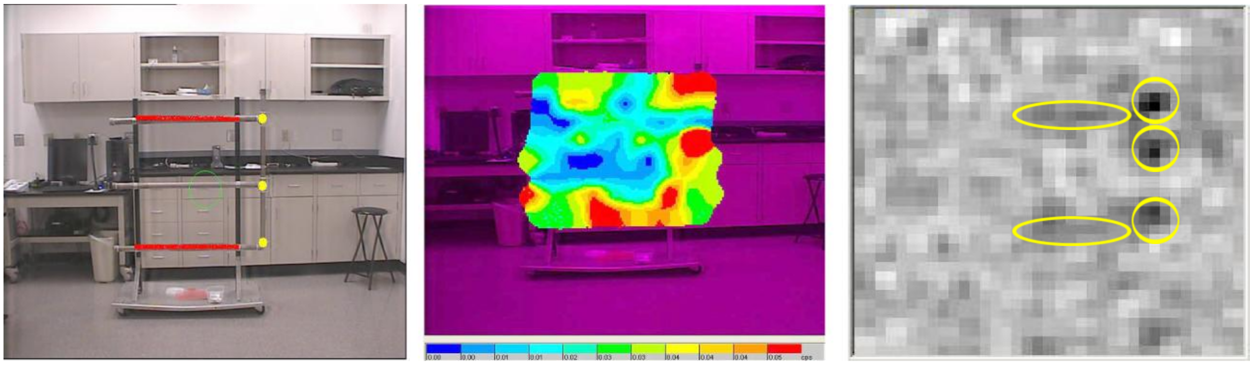

Figure 11. Results from preliminary test. *Left* – Pipe array with three UF_4 bulk sources (yellow) and two U_3O_8 line sources (red). *Middle* – RadScan image – pinhole imager. *Right* – Coded aperture image (yellow lines added manually).

Additional tests with the coded aperture instrument were done using different mock-up sources while maintaining the exact geometry of the pipe array measurement: ~3.8 m source-detector distance, ~7.5 cm mask-detector distance (focal length), and ~7 cm pixel size. Results for the first mock-up, a small round duct, are shown in Fig. 12. Inside the duct is a 177.5 cm U_3O_8 line source at 65% enrichment containing 8.06 g uranium. The output image successfully portrayed the line source inside the duct. Furthermore, a hot spot (in dark black) was observed because two line sources overlapped at the far left end of the duct. The computed source length was ~177 cm.

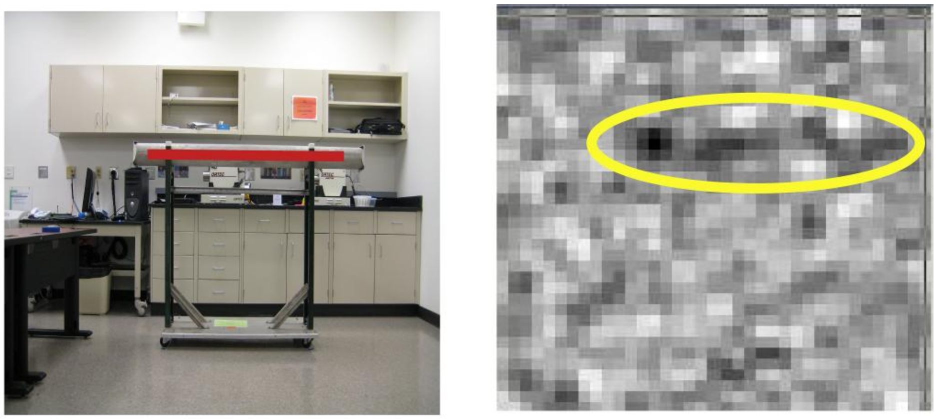

Figure 12. Experimental setup and results from first mock-up. *Left* – Experimental setup for the small round duct. The red represents the U_3O_8 line source inside the duct. *Right* – Radiometric image from the coded aperture after 1 h count.

Implementation Challenges

Upon visiting a facility in South America, for which a field trial is planned, technology developers realized the difficulties concerning the logistics required to move the instruments from the United States to the facility and then to operate them in a harsh environment. Improvements to both gamma-ray imaging systems are needed, and technology developers will be focusing their effort on making their systems transportable and sturdy.

Additionally, several measurements must be conducted with the gamma imagers to address real safeguards issues such as measuring pipes in different sizes, widths, thicknesses and with different types of materials and amounts.

Conclusions

The principle of combining outputs from two different technologies has been proven and demonstrated; images generated by the 3D laser scanner and gamma-ray imagers can be combined. The project is following its course on schedule. Improvements to both gamma-ray imaging systems are currently under way. A 3D laser scanner is now available for use. Additional measurements with gamma imagers combined with the 3D laser scanner are scheduled to be conducted in July and August 2009. These measurements will take place in a shut down demonstration facility at ORNL, where the instruments are expected to perform in an environment similar to that of a real facility.

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