Facility scale in-situ source localization and assay via a sparse ^{3}He neutron detector array: enhancing nuclear material control and accounting in nuclear fuel cycle facilities

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Abstract

At Los Alamos National Laboratory (LANL), the Dynamic Material Control (DYMAC) project has been established to enhance the LANL Plutonium Facility's manufacturing, research agility, efficiency, and to improve nuclear security by modernizing, streamlining and optimizing quantitative nuclear material measurements and Nuclear Material Control and Accounting (NMC&A). Challenges such as the complex dynamic nature of the radiation background, due to the continuous movement of nuclear items between glove boxes, can limit the efficacy of in-line NMC&A techniques in a nuclear production environment. In this paper, we develop an approach to in-situ facility scale source tracking to address this dynamic environment by developing a test bed measurement system which consists of a sparse array of ^{3}He neutron detectors located in proximity to an arrangement of glove boxes. Real time continuous neutron count rate data from the detectors are used for tracking the position and neutron emission rate of a number of ^{252}Cf items simultaneously. Several algorithms have been developed to analyze these in-situ measurements including: 1) a template matching algorithm which uses a set of calibration measurements to characterize the radiation field produced by a source without high-fidelity modeling, 2) an iterative deconvolution algorithm which uniquely separates the radiation of each source from their combined background to improve the solution accuracy, and 3) a reduced order radiation model which quickly projects the radiation field produced by the combined sources to the rest of the room. The system's performance was evaluated on its ability to detect a number of ^{252}Cf items emitting neutrons with their neutron emission intensity and position within the test bed facility. Results such localization spatial resolution, and neutron emission rate dynamic range will be presented.

Introduction

Nuclear material Control and Accountancy (NMC&A) of nuclear material inventories is vital to any facility processing nuclear material. Accidental diversion of material can represent a safety risk to the public, and intentional diversion of material by malicious actors can result in the development of weapons. For these reasons, nuclear processing facilities must have in place a reliable and efficient in-line NMC&A system that acts also as deterrence. NMC&A is based on various nuclear assay techniques which typically rely on neutron and gamma detection. These measurements can be challenging in a busy facility as a dynamic radiation backgrounds, due to the continuous movement of nuclear materials, may limit the accuracy of the measurements. Assay of nuclear material can be performed in an isolated room, but significant contamination and exposure risks make the movement of nuclear material between processing and measurement rooms very resource and labor intensive. At Los Alamos National Laboratory (LANL), the Dynamic Material Control (DYMAC) project has been established to developed and test emerging technologies and approaches to enhance the reliability and efficiency of NMC&A in a dynamic nuclear material production environment through real-time nuclear material situation awareness on item by item basis and real time 3-dimensional dynamic background measurement and evaluation.

In this paper, we report on the development of an approach to in-situ facility scale source tracking performed to by developing a test bed measurement system which consists of a sparse array of ^{3}He neutron detectors located in proximity to an arrangement of glove boxes. Real time continuous neutron count rate data from the detectors are used for tracking the position and neutron emission rate of a number of nuclear material items. By distributing an array of neutron detectors in a room, multiple sources can be tracked both by position and neutron emission strength. With the state of the room thus known, the count rates contributed by any particular source can be subtracted out from assay measurements performed in the room, removing the need for costly material transport to special assay rooms. Such real-time accountancy further provides a historical record of material movement in the facility, supporting confidence in the declared inventory and enhancing the facility's security posture by enabling playback of anomalous inventory events. An overview of the DYMAC project is presented in the INMM/ESARDA joint conference by the team [1], in conjunction with other papers of the team on results of the project [2, 3]. It is also worth noting here cite work of other international groups working on related research activities [1, 2].

Experiment Setup

A "testbed" mock nuclear facility is established in which nuclear material can be manipulated purely for the investigation of this study. The room is designed to be configurable in a wide variety of setups. For this work, the room is set up with four mock gloveboxes representing environments where nuclear material might be processed. The gloveboxes are named A, B, C, and D as illustrated in Figure 1. Gloveboxes C and D have double the working space of gloveboxes A and B to provide some variety and more broadly encompass processing facilities in general.

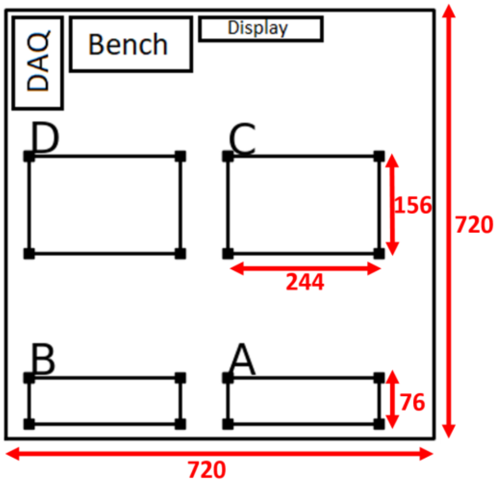

Figure 1. Testbed diagram showing four mock gloveboxes and neutron detectors (in black squares) on the corner of each glovebox. Gloveboxes A and B are 244 cm x 76 cm, and gloveboxes C and D are 244 cm x 156 cm. On top are the data acquisition system (DAQ), and a bench and a display for the operator.

Single-tube gas-filled ^{3}He proportional neutron detectors are placed on the corners of each glovebox as illustrated in Figure 2. The tubes are pressurized to 4 atm ^{3}He partial pressure and surrounded by a square cross-section high-density polyethelyne (HDPE) block of 8 cm on each side and wrapped in a 0.04cm thick sheet of Cadmium. Each detector assembly is encased in an aluminum housing which provides a mounting surface to interface with the extruded aluminum structural members of the gloveboxes. The online data acquisition system is able to record listmode data from each detector, providing a timestamp for every neutron detected.

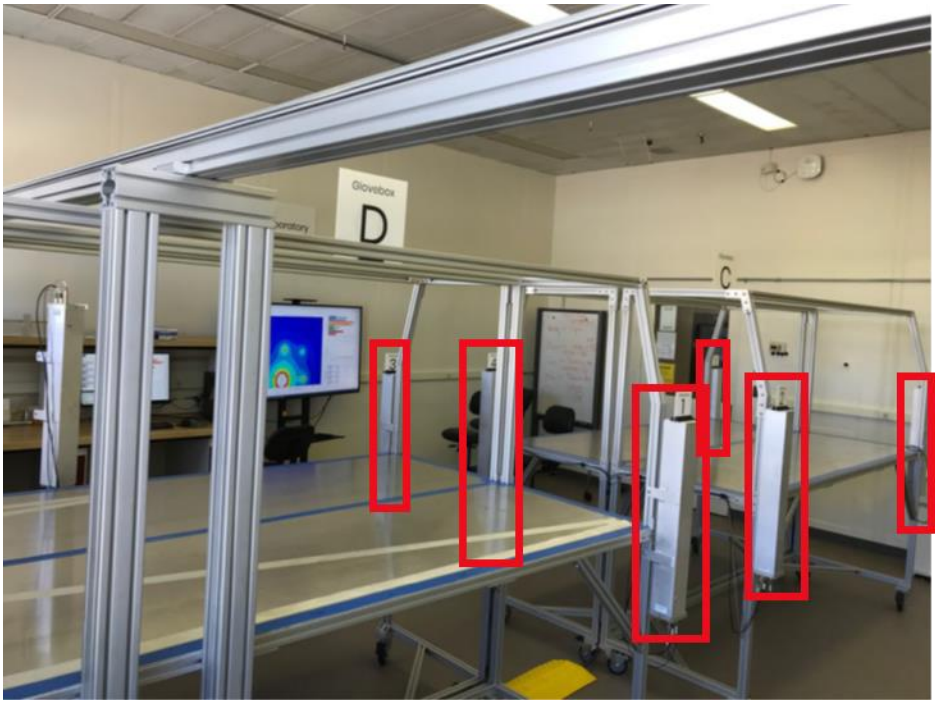

Figure 2. Picture inside the testbed. Single-tube ^{3}He detectors are highlighted in red.

Neutron sources of varying neutron yields, comprised of either Plutonium item or ^{252}Cf neutron sources, are then moved throughout the testbed, and analysis algorithms are written to process data from the detectors in real time, deconvoluting position, neutron emission of multiple sources simultaneously.

Methodology

The algorithm for deconvoluting multiple sources is comprised of four parts. First is an algorithm which localize a single source within a particular "zone". In the case of the testbed, each of the four gloveboxes is considered a zone. Second is a model which, given a source in the room, can project the neutron count rates that source will contribute to each other detector in the room. Third is a deconvolution scheme which iteratively makes independent single source predictions in each zone and then subtracts the projected count rates from each source on each zone, based on superposition, to converge on a final solution. Fourth is a thresholding algorithm which removes artifacts we refer to as "ghost sources".

For the single source localization algorithm, a template-matching scheme is chosen. In this scheme, the local detector count rates for a particular zone are normalized to their average. That normalized set of count rates is then compared to a set of 144 measurements taken in the room with a ^{252}Cf neutron source when it was set up. Those measurements are the "templates", and whichever template is most similar to the measurements taken in the room at any given time is assigned as the location of the source. To reduce setup time, the template measurements are taken on a relatively coarse mesh spaced roughly 25cm x 25cm, and an artificial template set is generated by linearly interpolating a 5cm x 5cm mesh from the measured coarse mesh. Once a template is selected to establish the position of the source, the source's strength is established by dividing the non-normalized measured neutron count rates by the template count rates and multiplying that by the known strength of the source used for the template measurement. A local zone prediction is thus made for both the source strength and source position.

The neutron field projection model is also based on the template database. By looking up the count rates a known source had on the detectors in the room, the same count rates are projected from the predicted source, multiplied by the ratio of the strength of the known template source and the predicted source.

The iterative deconvolution scheme is perhaps best described by a simplified example of two zones A and B, each with a source inside. In the initial prediction of each zone, the predicted strengths will be too high because each zone is getting counts from the other zone. In the second iteration, counts in B are reduced by the predicted count rates the source in A would contribute to them, and counts in A are reduced by the predicted count rates the source in B would contribute to them. Because the first prediction was too high, too many counts will be subtracted in the second prediction, meaning the second will be too low. However, the second prediction will be more accurate than the first. The third prediction is then made based on the sources predicted in the second iteration, and so on until a convergence criteria is met. In the current testbed setup, a convergence criteria of <1% change between iterations is used.

The thresholding aspect of the algorithm is required for zones which have no source present in them. In a real-world environment, the algorithm can produce imperfect source predictions, often leaving residual counts in some empty zones even after the predicted background is removed. The algorithm will try to account for these residual counts by predicting very weak sources in those zones. These sources can be removed by establishing a threshold source strength such that any predicted source below the threshold is considered an artifact. This necessarily means that no real source weaker than the threshold value can be detected. Some effort has gone into characterizing the nature of ghost sources based on the strength of other sources in the room and amount of time data is collected over. In the current testbed setup, a dynamic threshold is used based on these variables, but a static user-chosen threshold has also been used in the past and works equally well if the user knows a priori the weakest sources which will be present in the area.

A fifth algorithm is also used in the testbed which assists with data visualization and real-time situational awareness – a reduced order model fitting the neutron field count rate in the 3-D volume. Illustrated in Figure 3, curve fit model of the form A/r^B where A and B are the fitting parameters and r is the distance from the source is fit to the template database measurements taken in the testbed, composed of 2300 measurement points. With this simplified model, a contour plot of the neutron field count rate distribution in the entire room can be generated in real-time per each neutron source.

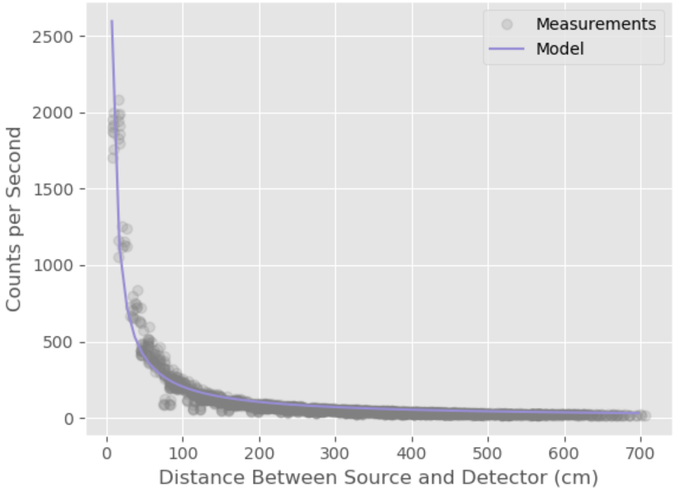

Figure 3. Performance of the neutron field model vs a mesh of 2300 measurements in the testbed gloveboxes.

Results

Illustrated in Figure 4, an experiment is conducted by placing four ^{252}Cf sources in the testbed, one in each of the four gloveboxes. The positions of the sources are not prescribed to be laid directly on the template grid. To further challenge the algorithm, sources with a relatively drastic strength disparity are chosen resulting in a factor of 11 ratio between the neutron yield of the weakest and strongest source. Red crosshairs in the plot illustrate the predicted source locations, and the colored contours represent the neutron field predicted by the reduced order model.

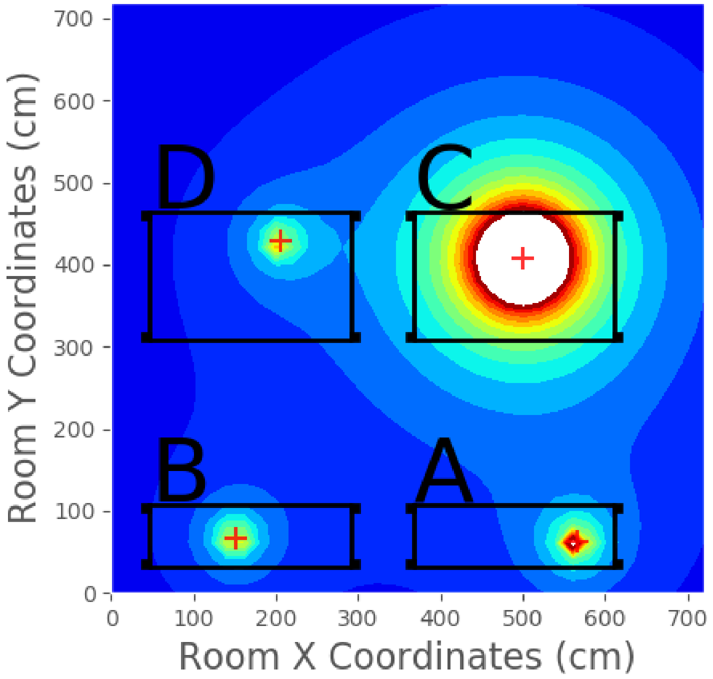

Figure 4. Predicted locations of four sources in the testbed and contours illustrating the neutron field density. This can be generated in real-time.

The details of the source strengths and positions and the algorithm's predictions are illustrated in Table 1. The average absolute error in predicted source neutron emission rate, in neutrons per second, is 4.30% and the average position prediction error is 4.45 cm with maximum errors of 10.14% and 13.15cm respectively. The position error of the source in glovebox B is greater than the 5 cm mesh size of the template database, illustrating that the algorithm does not always place the source in the nearest position. It is also worth noting that the high dynamic range, i.e. ratio of the neutron yield among sources, can reduce the algorithm's ability to identify weak sources in the same test bed. The weakest source which has been successfully localized in the testbed to date has a strength of 5,100 neutron per second (n/s). The largest dynamic range between ^{252}Cf neutron sources successfully parsed to date has been a factor of 33. Neither of these limits are considered fundamental limits but only the limits found to date by measurement based on the availability of sources for the measurements.

Table 1. Results of experiment comparing actual source neutron yields and locations to predicted yields and locations.

Actual				Predicted				Error	
Yield (n/s)	Zone	Local X (cm)	Local Y (cm)	Yield (n/s)	Zone	Local X (cm)	Local Y (cm)	Yield (%)	Position (cm)
70910	A	46	30	77122	A	45	30	-1.98%	1.00
78680	B	142	22	68692	B	140	35	-3.13%	13.15
596300	C	111	98	584742	C	110	100	-1.94%	2.24
51740	D	86	119	56988	D	85	120	10.14%	1.41

Conclusions

The algorithm presented is successful in localizing multiple ^{252}Cf neutron sources simultaneously and predicting their yields, in real time. This is a requirement for an efficient NMC&A system. By successively predicting and background subtracting, individual sources can be deconvoluted from a complex background in real time with no a priori knowledge of the number or strength of the neutron sources present. The algorithm presented performs well on the scale of a single facility room, and it scale according to the number of glove boxes and detector for different facility. Further work will investigate algorithms which span multiple rooms and include background sources which are outside of the glove boxes such as in trollies that move sources between rooms. Further developments of the work presented include to evaluate machine learning algorithms, and the introduction of gamma detector systems that provides a further signature of nuclear material to be used.

Acknowledgments. This work was supported by the Laboratory Directed Research and Development (LDRD) program at Los Alamos National Laboratory.

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