Hybrid Monte Carlo/Deterministic Methods for Active Interrogation Modeling

Douglas E. Peplow, Thomas M. Miller and Bruce W. Patton

Oak Ridge National Laboratory, MS 6172, P.O. Box 2008, Oak Ridge, TN 37831 peplowde@ornl.gov

INTRODUCTION

Scanning arriving cargo containers for illicit nuclear material is a current goal of the U.S. Homeland Security Department. This goal addresses shipments by trucks, airplanes, large cargo ships, and small vessels. One method to detect fissionable material currently under study by the U.S. Department of Energy and other agencies is active interrogation—a system that uses a radiation source, such as a collimated beam of neutrons or photons, to scan cargo containers and detect the products of induced fissions from any fissionable material. Getting particles to the fissionable material and then detecting the fissions can be extremely difficult because of attenuation in the materials themselves and the large distances between the source, the fissionable material, and the detector(s).

Computer simulation is essential to designing effective detection systems, a process that requires evaluating a wide variety of sources, detectors, designs of cargo containers, and possible materials that could be used to conceal nuclear material. Analogous to the physical radiation detection difficulties described above, computer simulations of radiation transport have difficulty calculating how many particles travel from the source to the fissionable material and then back to the detector, compared with the number of particles that interact elsewhere in the container. To reduce the statistical uncertainties in these simulations, prohibitively long calculation times are required. Long compute times severely limit the number of different parameters that can be explored in evaluating and designing active interrogation systems. If Monte Carlo simulations of active interrogation systems could be performed hundreds of times faster, dramatic improvements in design would be realized and optimization studies using more-detailed models could be completed.

This paper describes some preliminary work in applying automated variance reduction using hybrid Monte Carlo/deterministic methods. The MAVRIC sequence[1], part of ORNL's SCALE package of codes used for criticality, shielding, and reactor analysis, uses a coarse-mesh discrete ordinates calculation to determine the space- and energy-dependent importance parameters for a detailed Monte Carlo simulation. The CADIS[2] method is used to compute both the target weight windows and a consistent biased source, both functions of space and energy. The MAVRIC sequence is automated —handling the calculations for the variance reduction parameters with only minor additional input from the user —and highly capable in terms of accelerating traditional source-detector problems.

DESCRIPTION OF THE ACTUAL WORK

Most applications in which the MAVRIC sequence has been successfully applied have been source-detector problems—where source particles are biased so that those moving towards the detector with energies that will contribute to the detector response are simulated more often than those moving away from the detector or those with inconsequential energies. Active interrogation problems differ from typical source-detector problems in that particles must travel from the source to the fissionable material, cause fission, and then secondary particles must travel to a detector. The weight window value that should be used to control splitting and roulette is no longer just dependent on space and energy but is also dependent on whether or not the particle has interacted in the fissionable material.

Storing two importance maps in memory at the same time could be impractical for large problems. Setting a trigger for when to use which map is not as straightforward as setting an interaction flag or using a particle time. Doing the latter may start biasing particles toward the detector too early, not allowing for deeper penetration into or completion of fission chains within the target material to occur. The approach used in this study is to break the problem into separate steps (source to target and target to detector) and fully develop biasing parameters for each.

For the first step, the simulation needs to be optimized for finding the fission rate in the target material. A mesh tally over the target material from this step is then converted into a source for the second step. The second step is then optimized for finding the detector response from both the original source and the target material.

Like most other active interrogation problems, a completely separate calculation also needs to be done without the target material to determine the detector response due to source particles interacting in other parts of the phase space. Variance reduction can also be applied to this problem as well.

An example of an active interrogation system is shown in Fig. 1. A 14.1-MeV 10^9 n/s isotropic source and a helium-filled detector sit on opposite sides of a 55-gal barrel. The goal is to compute the difference in detector signal between two water-filled barrels, with one also containing 25 kg HEU (an International Atomic Energy Agency significant quantity). A single calculation is done for the barrel containing only water and a two-step calculation is done for the barrel containing HEU.

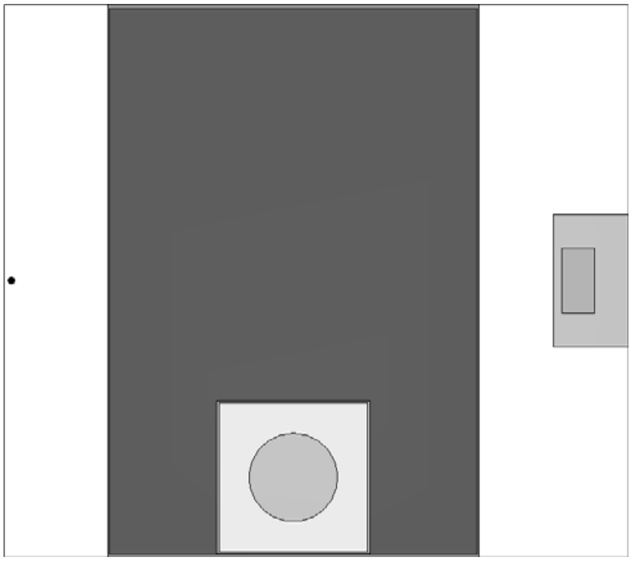

Fig. 1. Interrogation geometry for a barrel (57 cm diam, 85 cm high) with a source on the left side and a detector on the right. The HEU (25 kg) sits at the bottom of the barrel.

RESULTS

For the barrel without the HEU threat object, a one-hour MAVRIC calculation using a 200-group library with an importance map using a mesh of 19×26×26 and 27 groups gave a ^{3}He(n,p)^{3}H interaction rate of 6.43×10^3 (±0.4%) in the detector.

For the case with the HEU, the fission rate in the HEU was first calculated. A one-hour MAVRIC calculation using an importance map of 28×37×36 (with more mesh resolution in the HEU) calculated the fission neutron production rate mesh tally shown in Fig. 2. Note that the highest fission rates appear on the outer edge of the sphere, in the quadrant facing the source. The total neutron production rate in the HEU was found to be 4.16×10^7 (±0.7%) n/s.

The second step of the calculation using both the interrogation source and the fission source (1 hour, mesh of 28×42×40) calculated a detector interaction rate of 7.74×10^3 (±0.5%). This is 20% higher than the detector rate without the threat object.

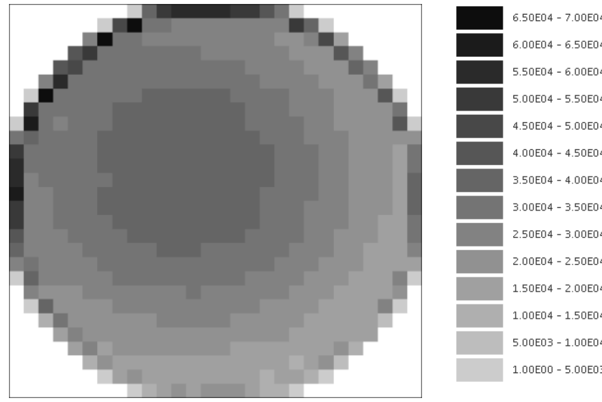

Fig. 2. Fission rate in the HEU

To obtain the same level of statistical uncertainty (~0.5%) with analog calculations, it is estimated that it would take 270 hours for the water-filled barrel and 390 hours for the barrel with the threat object. This is a considerable savings in calculation time. Results for this multi-step technique using other examples with different sources, different detectors, and different geometries (sealand container or small fishing boat) will also be presented.

REFERENCES

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