Hybrid Monte Carlo/Deterministic Methods for Active Interrogation Modeling

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Active Interrogation

• Find illicit nuclear material by sending in particles to induce fission and then detect the fission signature

• DHS Goal: Protect our Nation from Dangerous Goods
  – Scanning nearly 100 percent of arriving containers for illicit nuclear material
  – Implement a National Small Vessel Security Strategy to decrease the risk of weapons of mass destruction delivery via small vessels
  – Screening air cargo on passenger flights
**Active Interrogation is Difficult**

- Source strength is limited
- Large stand-off distances
- Large amounts of shielding
  - Hydrogenous material preferentially shields neutrons
  - High-Z (proton number) material preferentially shields photons
- Eventual designs will probably employ a mix of source types and a mix of detectors

**Active Interrogation is Difficult**

- Large range of cargos to be scanned

- Need to scan efficiently
Active Interrogation Simulation

- Variety of proposed systems
  - Gamma sources: bremsstrahlung, nuclear reactions
  - Neutron sources: D-T, D-D, nuclear reactions, photonuclear reactions
  - Exotic sources: muons
- Variety of detectors
  - Gamma: NaI, HP-Ge, organic scintillators
  - Neutron: $^3$He, BF$_3$, organic scintillators
  - Simple to complex (coincidence, n-correlation, etc)
- Variety of containers and cargos
- Simulation is needed to help evaluate and characterize proposed systems

Active Interrogation Simulation

- Everything that makes real active interrogation systems difficult also makes Monte Carlo simulation difficult
  - Large standoff
  - Heavy shielding
  - Huge parameter space
- Variance reduction is needed to reduce MC time for each simulation
**Variance Reduction in Monte Carlo**

- Bias the random sampling to spend more time on important particles and less time on unimportant particles.
- Used for several decades in all of the major Monte Carlo code packages.
- The difficult part is determining the importance of a particle to the final answer.
  - Usually requires some knowledge of the expected answer.
  - May require iteration to develop a good importance map.
- Well automated with the:
  - MAVRIC sequence in SCALE
  - ADVANTG tool for MCNP(X)

**CADIS Method**

**Consistent Adjoint Driven Importance Sampling**

Biased source and importance map work together


- Solve the adjoint problem using the detector response function as the adjoint source.
  \[ q^+ (\vec{r}, E) = \sigma_d (\vec{r}, E) \]

- Weight window target values are inversely proportional to the adjoint flux (measure of importance of the particles to the response).
  \[ \overline{w}(\vec{r}, E) = \frac{c}{\phi^+ (\vec{r}, E)} \]
CADIS Method

- We want source particles born with a weight matching the weight window targets

\[ w_0(\vec{r}, E) = \frac{q(\vec{r}, E)}{\hat{q}(\vec{r}, E)} = \overline{w}(\vec{r}, E) \]

- So the biased source needs to be

\[ \hat{q}(\vec{r}, E) = \frac{q(\vec{r}, E)}{\overline{w}(\vec{r}, E)} = \frac{1}{c} q(\vec{r}, E) \phi^+(\vec{r}, E) \]

- Since the biased source is a pdf, solve for \( c \)

\[ c = \int \int q(\vec{r}, E) \phi^+(\vec{r}, E) d\vec{r} dE \]

CADIS Method - Summary

- Define the adjoint source

\[ q^+(\vec{r}, E) = \sigma_d(\vec{r}, E) \]

- Solve for the adjoint flux \( \phi^+(\vec{r}, E) \)

- Find \( c \)

\[ c = \int \int q(\vec{r}, E) \phi^+(\vec{r}, E) d\vec{r} dE \]

- Construct weight windows and biased source

\[ \overline{w}(\vec{r}, E) = \frac{c}{\phi^+(\vec{r}, E)} \]

\[ \hat{q}(\vec{r}, E) = \frac{1}{c} q(\vec{r}, E) \phi^+(\vec{r}, E) \]

- Run the Monte Carlo
**Approach**

- Split the problem into several parts
  - Source to threat object
  - Threat object to detector(s)
  - Active background: Source (to whole geometry) to detector
- Optimize each separately with its own importance map
- The ‘target’ of one step becomes the source in the next step

**Example Studies**

Several Representative Models using various sources, container types, shielding materials, detectors

- D-T neutron source, 55 gallon drum, detect neutrons
- D-D neutron source, 40 ft container, detect neutrons and gammas
- Bremsstrahlung photon source, fishing trawler, detect neutrons
55 Gallon Barrel Scanner

- Barrels on a conveyor belt pass between a source and detector
  - D-T neutron source: 14.1 MeV, isotropic, S=10^9 n/s
  - He^3 detector, count rate is
    \[ \int \phi(E) \Sigma_{He(n,p)}(E) dE \]
  - Barrels are filled with water

- 25 kg HEU in balsa box (to avoid criticality)

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55 Gallon Barrel Scanner

- Analog Results

<table>
<thead>
<tr>
<th>Detector Count Rate</th>
<th>Time</th>
<th>FOM</th>
<th>Relative uncert</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>rel unc</td>
<td>(min)</td>
<td>(min)</td>
</tr>
<tr>
<td>Without HEU</td>
<td>6399</td>
<td>1.7%</td>
<td>1200</td>
</tr>
<tr>
<td>With HEU</td>
<td>7918</td>
<td>2.3%</td>
<td>1200</td>
</tr>
</tbody>
</table>
55 Gallon Barrel Scanner

• Step 1: Determine fission source
  – Use original D-T source, 10^9 n/s
  – Allow fission multiplication
  – Mesh tally of fission neutron production, \( \int \phi(E) \nu \Sigma_f(E) dE \)
  – Bias for that mesh tally
  – Strength of 4.16 \times 10^7 n/s
  – Convert mesh tally into mesh source using 235U fission \( \chi(E) \)

• Step 2: Determine total detector count rate
  – Include original D-T source (10^9 n/s)
  – Include new mesh source (4.16 \times 10^7 n/s)
  – Do not allow fission multiplication
  – Bias for computing \( \int \phi(E) \Sigma_{\text{He}(n,\alpha)}(E) dE \) in the detector
55 Gallon Barrel Scanner

- CADIS Results

<table>
<thead>
<tr>
<th>Detector Count Rate</th>
<th>Time</th>
<th>FOM</th>
<th>Value</th>
<th>rel unc.</th>
<th>/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without HEU</td>
<td>6432</td>
<td>0.43%</td>
<td>61.33</td>
<td>867</td>
<td></td>
</tr>
<tr>
<td>With HEU</td>
<td>7742</td>
<td>0.53%</td>
<td>120.37</td>
<td>272</td>
<td></td>
</tr>
</tbody>
</table>

Speed-Up over Analog:
- Without HEU 300
- With HEU 139

40 ft Sealand Container

- Container 1 m above concrete floor
- Homogenous Material
  - PNNL hydrogenous (0.2 g/cm^3)
  - DHS iron/organic mix (0.4 g/cm^3)
  - PNNL high Fe (0.6 g/cm^3)
- Look for 25 kg HEU sphere
40 ft Sealand Container

• **Source:**
  – D-D, 2.45 MeV neutrons, isotropic

• **Detectors:**
  – NaI (gammas)
  – HP-Ge (gammas)
  – $^3$He (neutrons)

• **Neutrons and photons from fission**

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40 ft Sealand Container

• **Methods**
  – Two-Step CADIS
    1. Find fission source from U
    2. Find detector count rate from interrogation source and the fission source
  – Modified
    • Find detector count from fission source alone

• **Nine calculations**
  – Three materials
  – Optimized for three detectors
40 ft Sealnd Container

- Results for DHS Cargo (0.4 g/cm³) and HP-Ge detector

<table>
<thead>
<tr>
<th>Uranium</th>
<th>Time (min)</th>
<th>Count (Rx/s/Ci)</th>
<th>Relative Uncert.</th>
<th>MC FOM (/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog</td>
<td>Denovo</td>
<td>MC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>without</td>
<td>1442</td>
<td>9.365E+04</td>
<td>4.9%</td>
<td>0.287</td>
</tr>
<tr>
<td>with</td>
<td>1443</td>
<td>1.046E+05</td>
<td>4.5%</td>
<td>0.348</td>
</tr>
<tr>
<td>CADIS</td>
<td>70</td>
<td>643</td>
<td>9.901E+04</td>
<td>1.2%</td>
</tr>
<tr>
<td>fission rate</td>
<td>83</td>
<td>62</td>
<td>7.292E+07</td>
<td>0.4%</td>
</tr>
<tr>
<td>CADIS</td>
<td>104</td>
<td>465</td>
<td>9.963E+04</td>
<td>1.4%</td>
</tr>
<tr>
<td>fission</td>
<td>105</td>
<td>462</td>
<td>3.166E+03</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

Similar results for other cargo material/detector combinations

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40 ft Sealnd Container

- Photon flux inside the HP-Ge detector (Cargo: 0.4 g/cm³)

![Graph showing photon flux](image_url)
40 ft Sealand Container

- Neutron flux inside the $^3$He detectors (Cargo: 0.6 g/cm$^3$)

![Graph showing neutron flux](image)

40 ft Sealand Container

- Increase in count rate with HEU present

<table>
<thead>
<tr>
<th>Cargo Description</th>
<th>Sodium Iodide Detector</th>
<th>High-Purity Germanium Detector</th>
<th>Helium-3 Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>PNNL hydrogenous (0.2 g/cm$^3$)</td>
<td>4.7%</td>
<td>10.7%</td>
<td>1.3%</td>
</tr>
<tr>
<td>DHS iron/organic mixed cargo (0.4 g/cm$^3$)</td>
<td>2.8%</td>
<td>3.2%</td>
<td>2.3%</td>
</tr>
<tr>
<td>PNNL high iron mixed cargo (0.6 g/cm$^3$)</td>
<td>0.8%</td>
<td>1.1%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>
40 ft Sealand Container

• Speed up compared to analog calculations

<table>
<thead>
<tr>
<th>Cargo Type</th>
<th>Detector Type 1</th>
<th>Detector Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PNNL hydrogenous (0.2 g/cm³)</td>
<td>Sodium Iodide</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Detector</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>High-Purity</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>Germanium Detector</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Helium-3 Detectors</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>Detectors</td>
<td>87</td>
</tr>
<tr>
<td>DHS iron/organic mixed cargo (0.4 g/cm³)</td>
<td>Sodium Iodide</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Detector</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>High-Purity</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Germanium Detector</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Helium-3 Detectors</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Detectors</td>
<td>46</td>
</tr>
<tr>
<td>PNNL high iron mixed cargo (0.6 g/cm³)</td>
<td>Sodium Iodide</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Detector</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>High-Purity</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>Germanium Detector</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>Helium-3 Detectors</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>Detectors</td>
<td>64</td>
</tr>
</tbody>
</table>

Multiple Containers

• 4×6x3 array of 40 ft containers
  – Random mix of three homogenous cargos
Multiple Containers

Step 1: Bias neutrons toward HEU

Step 2: Bias neutrons toward detector

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Analog Result</th>
<th>MC Result</th>
<th>CADIS Result</th>
<th>FOM Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active background</td>
<td>3770</td>
<td>74</td>
<td>151 ± 0.3%</td>
<td>5811</td>
</tr>
<tr>
<td>Fission rate</td>
<td>5755</td>
<td>59</td>
<td>1440</td>
<td>140</td>
</tr>
<tr>
<td>Fission detection</td>
<td>5769</td>
<td>140</td>
<td>1440</td>
<td>5.4×10^{-5} ± 1.3%</td>
</tr>
</tbody>
</table>

Fishing Trawler

- **Source**: 20 MeV bremsstrahlung spectrum above 1 MeV
- **Detector**: $^3$He and plastic scintillator, 25 m from boat
- **Active Background**: photoneutrons
Fishing Trawler

1. Compute photonuclear reaction rate as a function of energy and space (group-wise mesh tally) for HEU, fish/ice mix and hull materials. Photon-only problem.

2. Convert mesh tallies of photonuclear reaction rate into neutron mesh sources.

3. Compute the fission neutron production rate in the HEU sphere from the three photonuclear neutron sources. Neutron-only with fission on.

4. Convert fission neutron production rate mesh tally into a neutron mesh source.

5. Determine detector response rates from the neutron sources:
   1. HEU fission neutrons
   2. HEU photo-nuclear effect neutrons
   3. fish/ice photo-nuclear effect neutrons
   4. hull photo-nuclear effect neutrons

   Neutron-only with fission off.

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**Fishing Trawler**

- **Step 1. Compute photonuclear reaction rate**

![Image showing photonuclear reaction rate as a function of energy and space for HEU, fish/ice, and Hull Steel.](image)

- **10 MeV photons**
  - HEU
  - Fish/ice
  - Hull Steel

- **Hours**
  - SN: 3
  - MC: 8
Fishing Trawler

• Step 3. Compute the fission neutron prod. rate in the HEU

![Fission rate map]

1 MeV neutrons

• Step 5. Determine detector response rates

<table>
<thead>
<tr>
<th>Source</th>
<th>Counts</th>
<th>Rel Unc</th>
</tr>
</thead>
<tbody>
<tr>
<td>He-3 (n,p)</td>
<td>1.44E+00</td>
<td>5.5%</td>
</tr>
<tr>
<td>plastic scint</td>
<td>5.68E+02</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

All neutron sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Counts</th>
<th>Rel Unc</th>
</tr>
</thead>
<tbody>
<tr>
<td>He-3 (n,p)</td>
<td>1.92E-07</td>
<td>16.5%</td>
</tr>
<tr>
<td>plastic scint</td>
<td>1.56E-04</td>
<td>10.2%</td>
</tr>
</tbody>
</table>

HEU fission only

Presentation slide
Fishing Trawler

- Initial results only, no comparison to analog yet
- Beam source – required new version of Denovo $S_N$ code
- Photo-nuclear data – not part of Standard SCALE libraries
- May need CADIS method that is space/energy/angle

\[
\bar{w}(\vec{r}, E, \hat{\Omega}) = \frac{c}{\phi^+(\vec{r}, E, \hat{\Omega})}
\]

\[
\hat{q}(\vec{r}, E, \hat{\Omega}) = \frac{1}{c} q(\vec{r}, E, \hat{\Omega}) \phi^+(\vec{r}, E, \hat{\Omega})
\]

Summary

- Multi-step approach works well
  - Uses one importance map/biased source per step
  - Could reuse similar first steps
- Active interrogation is a challenging problem
Future Work

• Further automation: determine if multiple importance maps could be in memory at once.
  – User describes source, intermediate goal and final goal
  – Sequence would find importance map for each step
  – In the MC, particles would switch which importance map to use based on event history
  – This approach may be needed for coincidence modeling
  – Drawbacks: memory, consistent target weights between maps

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