FW/CADIS-Ω: AN ANGLE-INFORMED HYBRID METHOD FOR DEEP-PENETRATION RADIATION TRANSPORT

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Project Background and Motivation

Background

Hybrid methods take advantage of the speed and uniform solution certainty of a deterministic transport calculation to accelerate a Monte Carlo transport calculation. A subset of hybrid methods have been developed for deep-penetration radiation transport. These methods are ideal for radiation protection, dosimetry, nonproliferation, and shielding applications. Of note are the consistent adjoint-driven importance sampling (CADIS) and forward-weighted CADIS (FW-CADIS) methods (henceforth FW/CADIS), for local- and global- variance reduction, respectively. These methods use the solution from the adjoint neutron transport equation to generate variance reduction parameters in space and energy.

Motivation

Many existing deep-penetration hybrid methods have been optimized for problems in space and energy, but not angle. Those that incorporate angle are either not widely accessible, only work for a small problem space, or require a custom transport suite. For a subset of problems where the anisotropy in the flux is important to the problem solution, many of these methods are not sufficient. We present a method that incorporates directional information from the forward flux into the adjoint flux used to generate variance reduction parameters for Monte Carlo. This method has been designed for adaptation into existing implementations of FW/CADIS.

FW/CADIS-Ω

Both CADIS and FW-CADIS use the solution from the adjoint neutron transport equation (NTE) to generate variance reduction (VR) parameters. Our method incorporates angle by constructing a weighted contributon formulation of the scalar flux.

Classic FW/CADIS:

$$\phi(\vec{r}, E) = \int \psi(\vec{r}, E, \hat{\Omega})\, d\Omega$$

FW/CADIS-Ω:

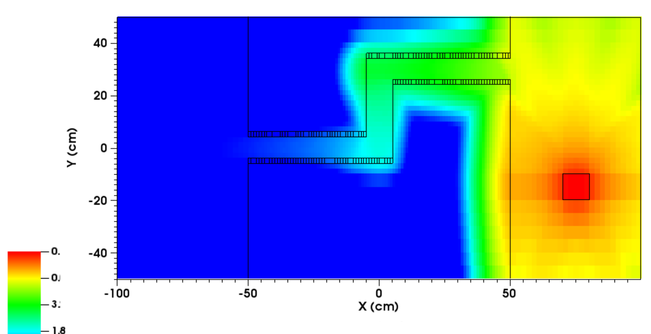
Uses angular flux→ more angular information is captured in importance map

$$\phi^{+}(\vec{r}, E) = \frac{\int \psi(\vec{r}, E, \hat{\Omega})\psi^{+}(\vec{r}, E, \hat{\Omega})\, d\hat{\Omega}}{\int \psi(\vec{r}, E, \hat{\Omega})\, d\hat{\Omega}}$$

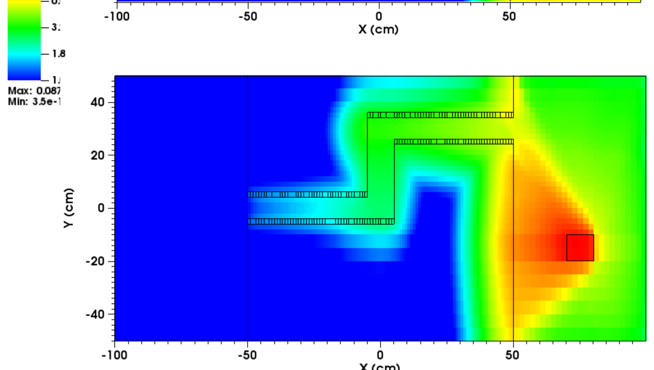
Generates adjusted adjoint scalar flux → can be adapted for existing hybrid methods

Weights adjoint by the forward flux → importance map includes direction of particle flow

Visualizing ϕ and ϕ^+:



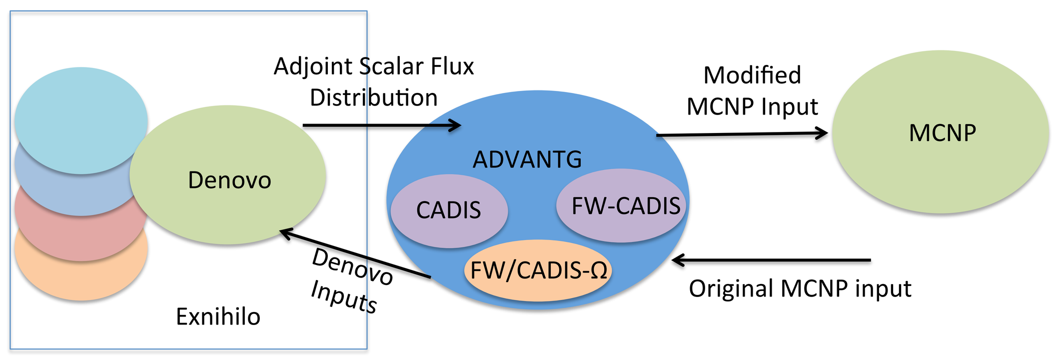
Top: adjoint flux map generated using ϕ distribution for lowest energy group (26^{th}) in the problem. This is the map used for traditional FW/CADIS



Bottom: adjoint flux map generated using ϕ^+ for lowest energy group (26^{th}) in the problem. Note the non-symmetry of the adjoint flux map, indicating that ϕ^+ incorporates direction of particle flow

Implementation

The Ω-methods have been incorporated into the ORNL transport software Denovo and ADVANTG.



Changes to the codebase(s):

- Ω-method to generate ϕ^+ is a module in **Denovo**, a discrete ordinates transport code in the Exnihilo codebase.
- **Denovo** altered to output ψ in addition to ϕ
- **ADVANTG** altered to call the ϕ^+ method module in CADIS-Ω and FW-CADIS-Ω modules to generate VR parameters for **MCNP**
- Adjusted MC input deck is generated with new VR parameters as output from **ADVANTG**.

Technical details:

- Implementation was done using **Python 2.7**
- Storage of ψ from Denovo transport is in **HDF5**
- ϕ^+ stored in **Silo** for analysis using **VisIT**

Because the Ω-methods are incorporated in Denovo, they can be readily adapted to other hybrid methods software that have CADIS and FW-CADIS.

Concluding Remarks

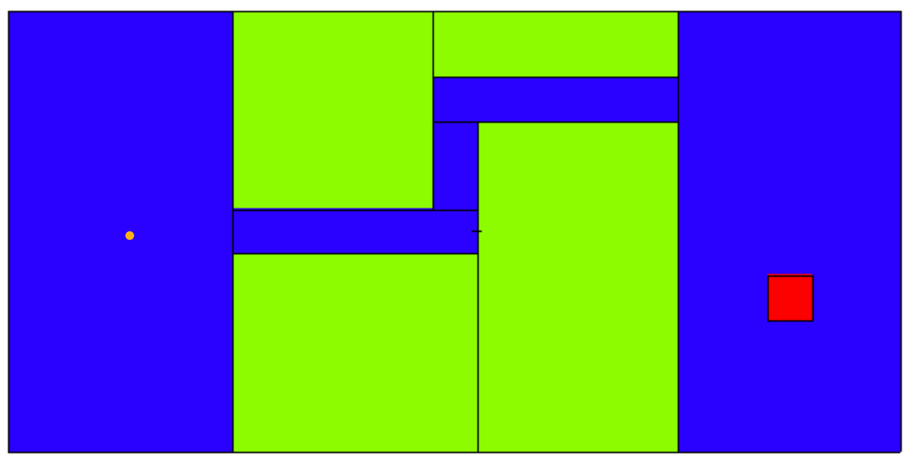
The CADIS Omega- method:

- Captures problem physics more effectively by normalizing the contributon flux by the forward flux.
- Demonstrates an ability to more evenly distribute the uncertainty distribution in an f4 tally
- Has significantly stronger performance than CADIS for a deep-penetration shielding problem.
- Exhibits a dampening of ray effects in regions where the forward and adjoint fluxes are perpendicular.
- Has effective capture of streaming behavior out of problem ducts.
- Does not completely negate low-importance regions (e.g. the region behind the detector in the void BC problem)
- FOM comparison to the naive MC maze is consistently lower; for other problems this may not be the case.

The full range of abilities for CADIS-Ω will be tested in a comprehensive problem suite of characterization and scaling tests (see Future Work). This suite will include:

- A vast range of flux anisotropy-inducing physics conditions
- Variations in deterministic (XS library, discretization type, quadrature type, quadrature order, P_N order) and Monte Carlo (tally type, tally resolution, tally discontinuity) transport parameters to determine method's robustness.

Results and Discussion



Simple maze problem. 100cm thick, 100cm tall, 100cm deep, concrete barrier with air duct penetration. Reflective boundary conditions, NaI detector (red), 10MeV monoenergetic point source (left, indicated with yellow dot for visualization).

Deterministic parameters: 136,500 mesh cells, 27 neutron energy groups, SC spatial discretization, QR quadrature set, quadrature order 10, 4 azimuthal angles, 4 polar angles, Pn order 3.

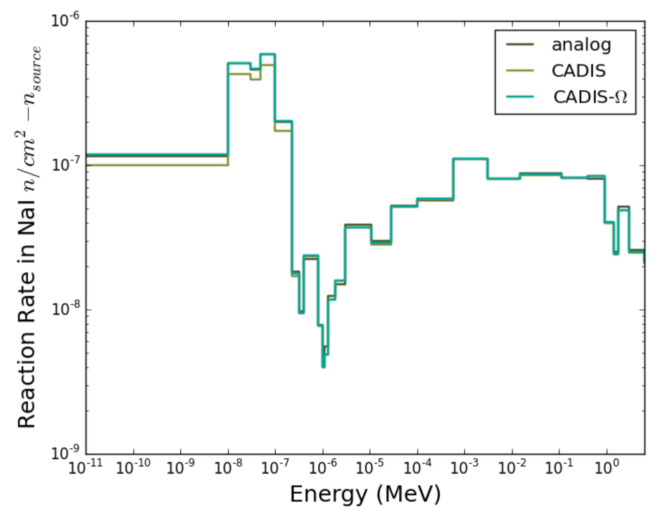
Monte Carlo parameters*: Tally response measured with f4 (track length) tally, measuring total reaction rate in the detector volume

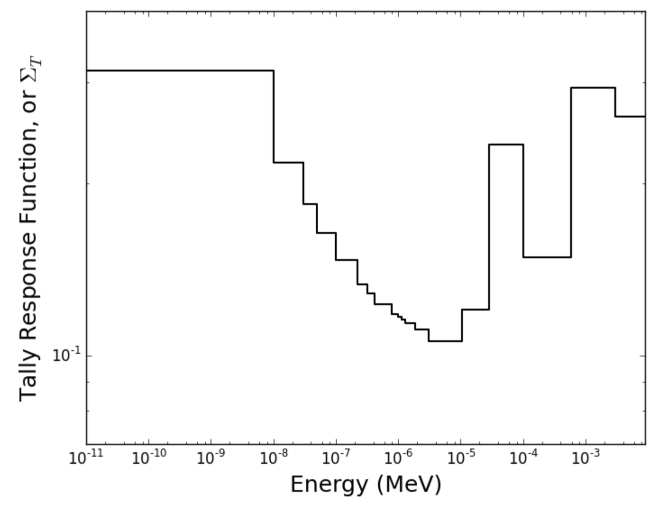
Table I: Method Performance Change with Quadrature Order

Quadrature Order	Type	MCNP time (minutes)	Denovo time (minutes)	FOM
Six	Analog	62.4	0.0	523.0
	CADIS	3325.5	22.0	2.20E-02
	CADIS-Ω	558.1	43.9	122.0
Ten	CADIS	483.4	41.5	5.1
	CADIS-Ω	408.9	83.0	145.0
Fourteen	CADIS	514.4	76.0	3.2
	CADIS-Ω	423.1	152.0	129.0

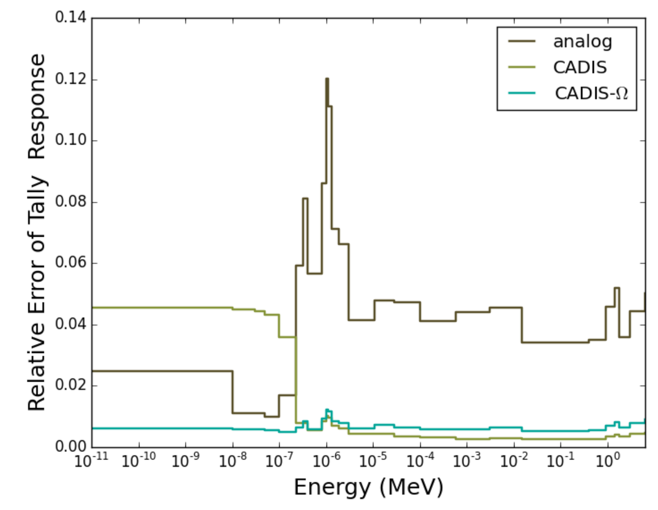
Table II: Method Performance Change with P_N Order

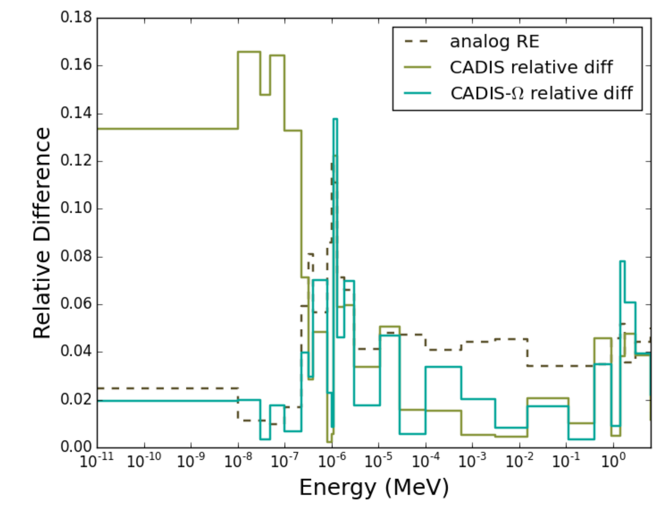
P_N Order	Type	MCNP time (minutes)	Denovo time (minutes)	FOM
Two	Analog	62.4	0.0	523.0
	CADIS	409.7	40.3	12.0
	CADIS-Ω	326.2	80.7	138.0
Three	CADIS	483.4	41.5	5.1
	CADIS-Ω	408.9	83.0	145.0
Four	CADIS	400.7	45.5	6.2
	CADIS-Ω	266.6	91.0	291.0





Upper left: Reaction rate in detector measured by differing methods. Note the largest discrepancies lie in low energy regions.
Upper right: Response function reference (cross section) sampled in NaI detector tally
Lower left: Relative error distribution in tally determined by differing methods. Note that CADIS-Ω appears to have a uniformly low uncertainty distribution while traditional CADIS does not capture low-energy physics as effectively.
Lower right: Comparison between the relative difference of CADIS and CADIS-Ω to the analog result. The relative error of the analog is provided for reference.

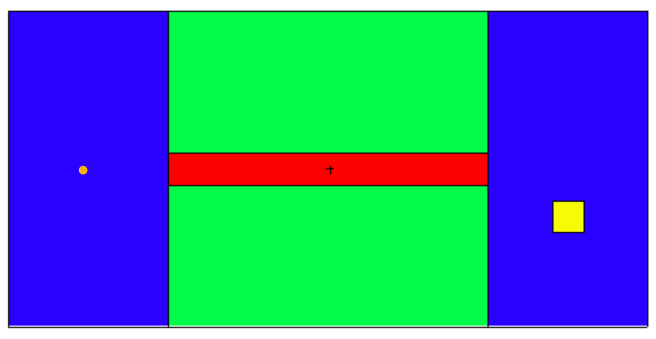


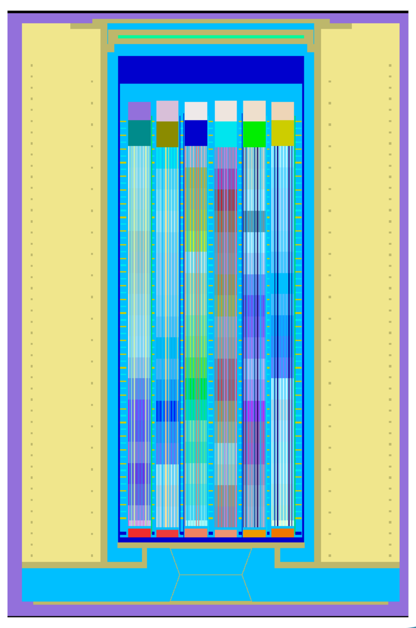


Notes:
* All Monte Carlo calculations were run with a 10 million particle constant. Timings for these problems varied between 60 minutes to ~1000 cpu minutes. The analog problem and several CADIS-Ω problems passed all statistical checks with this particle count, but several of the hybrid runs (both CADIS and FW-CADIS) did not pass all statistical checks. Common failures were that the variance of the variance exceeded 0.1 and the FOM exhibited a trend for part of the problem.
** An updated version of the paper corresponding to this poster is available at the publications page of munkm.github.io
*** The results in this paper are still preliminary

Future Work

Characterization tests: are simple, small-scale problems meant to be run quickly over a broad phase space to determine the flexibility and robustness of the omega methods.
Application tests: are larger-scale, more realistic, complex geometry, complex material composition problems designed for large-scale computing systems.





Top: Characterization test example. Includes a steel bar penetrating 1m of concrete with a point source and detector.
Right: Application test example of a high-fidelity, dry cask storage model. Streaming paths for particles exist in duct regions both above and below the fueled cannister region.

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