Chapter 1

Introduction

This dissertation covers the development, implementation, and characterization of a novel hybrid method for neutral particle, deep-penetration, steady-state, radiation transport in highly anisotropic problems. The method generates a forward-weighted adjoint scalar flux, which is then used to consistently generate variance reduction parameters for Monte Carlo radiation transport. Because of the incorporation of directionality into the adjoint scalar flux, the method has been named FW/CADIS-Ω. The name alludes to the lineage of the method, which builds on the Consistent Adjoint-Driven Importance Sampling (CADIS) [1, 3, 4, 2], and Forward-Weighted CADIS (FW-CADIS) [5, 6] methods. This research both develops a new method that can be used in problems with strong anisotropies and provides a novel analytical framework by which to characterize anisotropy characteristics of problems. This work advances the current state of hybrid methods and extends the availability of alternate hybrid methods in existing software.

1.1 Motivation

Radiation shielding is a realm of continued importance for nuclear engineering, nuclear security, and health physics applications. With the expansion of nuclear technology applications, the potential proliferation of nuclear materials, and the continued development of nuclear medicine, tools with which to predict the behavior of these systems are in ever-increasing demand. Over the course of many decades, radiation transport methods have been developed in two primary areas: stochastic (Monte Carlo) and deterministic.

These tools have the potential to be immensely powerful, but are not without their drawbacks. Monte Carlo methods have the benefit of modeling transport that is continuous in energy, space, and angle. A user can obtain results for any region in phase-space that one might desire. However, Monte Carlo methods also require adequate sampling in order to obtain a solution with sufficient precision. Adequate sampling depends on the number of particles transported to the tally region. The more particles that are run in a problem, the longer the computational time required. Depending on the complexity of the problem, this may be difficult, computationally demanding, very time consuming, or impossible.

Deterministic transport methods discretize the problem phase-space in space, energy, and angle. They iteratively converge on a global problem solution that is equally valid across the entire problem space, rather than a potentially localized tally location. Deterministic solvers tend to be much faster than Monte Carlo methods, but also lose the continuity in phase-space that is offered by Monte Carlo. Depending on the coarseness of the problem discretization, features of interest in the particle flux may be incorrect, obfuscated, or missed entirely.

Hybrid methods leverage the speed and uniform solution validity of deterministically-obtained transport solutions to bias Monte Carlo transport to more effectively sample in regions of interest. Biasing Monte Carlo to move particles to regions of interest more effectively is called variance reduction. Many existing implementations of hybrid methods automate the variance reduction process to speed up the time to a desired solution or to achieve a more uniform uncertainty distribution in the problem.

Hybrid methods have been designed for an assortment of applications, and none are universally applicable to all problem types. In particular, hybrid methods are wanting for a method well-suited for highly anisotropic, deep-penetration radiation transport applications. The work presented herein endeavors to provide a potential solution for such applications.

1.2 Research Objectives

This dissertation addresses a number of research objectives. The primary research goal is to:

- develop a hybrid method capable of generating variance reduction parameters for highly anisotropic, deep-penetration radiation transport problems.

Several supporting objectives accompany this goal. They are:

1. Propose a hybrid method that capitalizes on a solid theoretical framework and lessons learned from existing hybrid methods.

2. Implement the method in a software package such that it is transparent and reproducible.

3. Devise a rigorous and consistent set of metrics with which to quantify method performance.

4. Develop a suite of problems that have anisotropic behavior induced by the problem physics with which to characterize the method.

5. Run the method and existing hybrid methods on the suite of problems. Using the results obtained from these runs, compare the method's performance to exiting hybrid methods.

6. Investigate the sensitivity of the method to other angular-flux perturbing parameters, such as the angular discretization of the deterministic transport.

By addressing each of these objectives, the new method will be proposed, developed, implemented, and characterized such that its behavior in different problems is well-understood and the method is usable by interested parties that do not have the expertise of a developer or the author.

1.3 Outline of the Dissertation

The next several chapters of this dissertation covers the relevant background, the pertinent theoretical basis, and the numerical results that address the research objectives outlined in Section 1.2. Chapter 2 provides a comprehensive background on the theoretical basis on which Monte Carlo methods, deterministic radiation transport, and hybrid methods for radiation shielding are founded. In so doing, it provides context for the existing gaps for generating variance reduction parameters in highly anisotropic, deep-penetration radiation transport problems. It further highlights the most effective hybrid methods that can be applied to non-anisotropic, deep-penetration radiation transport problems.

The conclusion of Chapter 2 demarcates the transition from theoretical background work to the novel contributions of this project. Building on the knowledge presented in Chapter 2, Chapter 3 presents an overview of the theoretical basis of the method developed in this research. The theory contained in this chapter contributes to the larger body of hybrid methods research. This chapter also covers the software used for this project, and how it was modified to incorporate the novel theory presented herein. Next, Chapter 4 presents several problems with which the method is to be characterized. The results from these problems inform a parametric angle-informed study, presented in the latter portion of the chapter. Finally, Chapter 5 draws from the results presented in Chapter 4 to discuss the performance of the new method, summarize what was learned from the method characterization, and suggest future paths forward for future hybrid methods research.