Representing Range Compensators with Computational Geometry in TOPAS

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ABSTRACT

In a proton therapy beamline, the range compensator modulates the beam energy, which subsequently controls the depth at which protons deposit energy. In this paper, we introduce two computational representations of range compensator. One of our compensator representations, which we refer to as a *subtraction solid*-based range compensator, precisely represents the compensator. Our other representation, the *3D hexagon*-based range compensator, closely approximates the compensator geometry. We have implemented both of these compensator models in a proton therapy Monte Carlo simulation called TOPAS (Tool for Particle Simulation). In the future, we will present a detailed study of the accuracy and runtime performance trade-offs between our two range compensator representations.

INTRODUCTION

Proton therapy is one of the best methods available for treating cancer [1]. The number of proton facilities is steadily increasing, and proton therapy is entering the mainstream of radiation therapy. TOPAS (Tool for Particle Simulation) is a four year NIH-funded project of SLAC, University of California, San Francisco (UCSF) and Massachusetts General Hospital to make Monte Carlo particle transport simulation faster and easier to use for proton therapy [2] [3] [4]. TOPAS enables researchers and clinicians to refine proton therapy delivery system designs and individual patient treatment plans to improve proton therapy's therapeutic ratio (improved tumor control, reduced side effects). TOPAS offers a collection of ready-made geometries for modeling proton therapy beamlines, and TOPAS uses Geant4 for fundamental physics processes.

In most proton therapy facilities, an extensive beamline lies between the proton source and the patient. This beamline includes components such as collimators, magnets, a range modulator, scatterers, and a range compensator. The range compensator (or simply *compensator*) sits close to the patient. The fundamental purpose of a range compensator is to modify the proton beam energy so that the protons deliver energy to the correct location in a patient. This study seeks to represent compensators with computational geometry. While a wide variety of computational geometry methods could be applied to compensator representation, we focus on fast and accurate methods. This paper presents two compensator representations, which the authors have recently implemented in TOPAS.

BACKGROUND

The Range Compensator

In proton treatment facilities, medical staff typically prescribe a radiation dose (in Greys) to a patient's tumor. To ensure that the correct dose is delivered to the correct location, the

protons must have a specific energy. The necessary energy may vary within the treatment region. A *range compensator* allows a beamline to deliver protons with the correct energy (and corresponding depth of deposition).

In many proton therapy facilities, a non-Monte Carlo treatment planning software such as XiO [5] designs a unique range compensator for each patient. In some facilities, medical physicists use a Monte Carlo simulation such as TOPAS to validate the compensator design. Therapy facilities typically construct compensators by using a milling machine to drill a number of holes out of a cylinder of Lucite or other clear plastic. Each drill hole may have a unique depth, such as in Figure 1. The thickness of the Lucite proportionally reduces the protons' energy. Lower-energy protons deposit most of their energy at a shorter depth in the patient than higher-energy protons. In short, the range compensator modulates the beam energy, which subsequently controls the depth at which protons deposit energy.

Subtraction Solids in Geant4

Geant4 supports boolean solid combinatorial geometry [6]. Subtraction solids are a type of Geant4 boolean solid. Subtraction solids enable a small solid to be cut out, or *subtracted*, from a larger solid [7]. The pseudo code in Figure 2 serves as a simple example of subtraction solid geometry. As shown in Figure 3, Geant4 also allows nested subtraction of solids. In addition, subtracted solids are allowed to overlap. Therefore, for the example in Figure 3, Geant4's ability to track particles is not impaired if the subtracted cylinders, `smallCylinder1` and `smallCylinder2`, overlap. In contrast, geometrical components that are not comprised of boolean solids are not allowed to overlap in Geant4.

RANGE COMPENSATOR MODEL WITH SUBTRACTION SOLIDS

Given the compensator milling machine instructions in .Decimal format [8], we subtract each drill hole from the solid Lucite cylinder. We subtract the cylinders in the same order that the milling machine would drill the cylinders. Thus, we produce an exact model of the real compensator. The pseudo code in Figure 3 constructs a compensator comprised of a bigCylinder with n drill holes subtracted. Figure 4 offers a Geant4 visualization [9] of a subtraction solid compensator with twelve holes subtracted.

Our (unpublished) preliminary results show that, especially for compensators with fifty or more drill holes, tracking particles through a subtraction solid-based compensator is quite slow. To remedy this, we present a hexagon-based compensator approximation in the next section.

"3D HEXAGON"-BASED RANGE COMPENSATOR APPROXIMATION

In this section, we present an approximate compensator representation. We approximate the drill holes with a collection of "3D hexagons," as shown in Figure 5. Each 3D hexagon has the depth of the drill hole that it represents.

We choose 3D hexagons, because they can be clustered without overlap or gaps. (Recall that, while boolean solids allow overlap, other forms of Geant4 geometry do not allow overlap.) The lack of overlap among the hexagons allows us to insert a volume of air in the shape of each 3D hexagon into the Lucite cylinder. However, unlike the precise compensator model produced with subtraction solids, the 3D hexagon model does not correctly represent the drill hole depth in regions where drill holes overlap.

Our preliminary results show that particle tracking through a hexagon-based compensator is as up to twenty times faster than through a subtraction solid-based compensator. We will present the finalized version of these results in a future study.

CONCLUSIONS AND FUTURE WORK

In this paper, we introduced two range compensator representations, which we have implemented in TOPAS. In the near future, we will present a detailed study of the accuracy and runtime performance trade-offs between our two compensator representations.

ACKNOWLEDGMENTS

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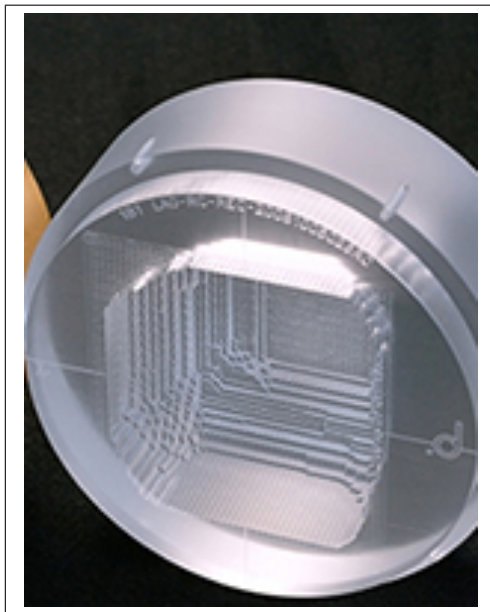
FIGURES

Figure 1: Example range compensator

```
newSolid = bigCylinder - smallCylinder
```

Figure 2: Pseudo-code for simple subtraction solid example

```
newSolid1 = bigCylinder - smallCylinder1
newSolid2 = newSolid1 - smallCylinder2
...
Compensator = newSolid(n-1) - smallCylinder(n)
```

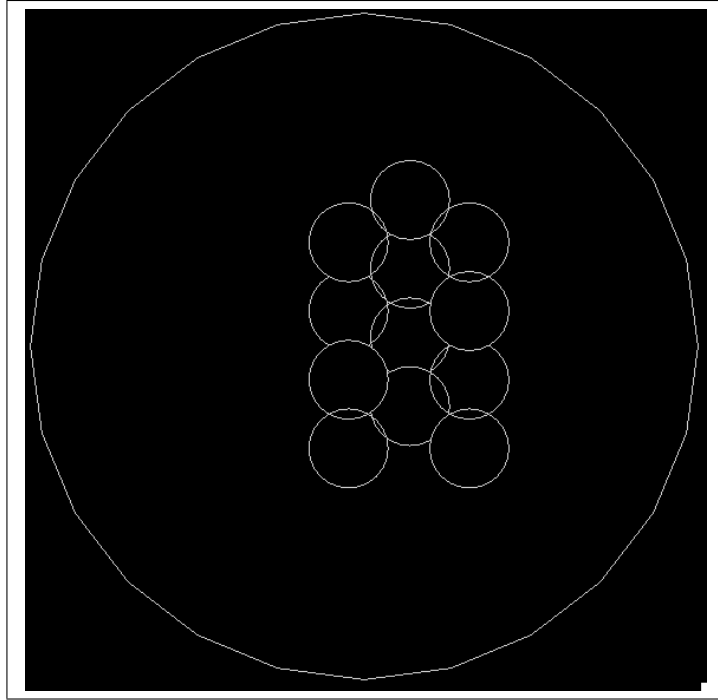Figure 3: Pseudo-code for repeated subtraction solid example
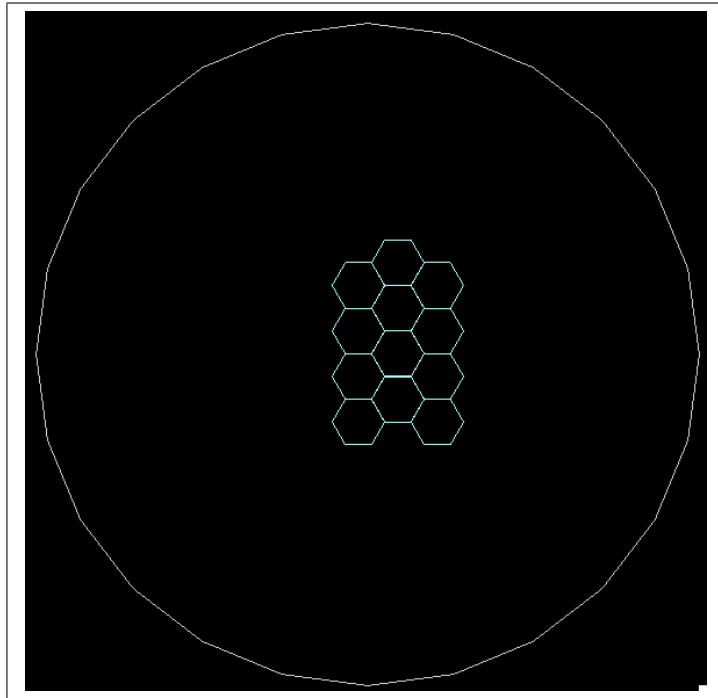
Figure 4: Compensator modeled with subtraction solids

Figure 5: Compensator modeled with 3D hexagons