Study of dynamic geometry in simulation and reconstruction of liquid-based detector

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Abstract. The non-uniformity of liquid in a detector is difficult to be described with the traditional detector description method used in Geant4. To solve the simulation and reconstruction problem with dynamic and non-uniform liquid-based detector, a method of combining GDML and tessellated 3D modeling is put forward to export the detector geometry information from computational fluid dynamics simulation software and import it into the detector simulation software. This method can be used to study the effects of non-uniformity on detector performance. It can be further used to solve other dynamic geometry-related problems in particle and nuclear physics experiments.

1. The liquid-based detector

With the discovery of Higgs boson in 2012, the standard model (SM) has been proven to be a very successful theory. However, several experimental results such as neutrinos having mass indicates the imperfect of SM. In recent years, the intensity frontier in high energy experiments has become more and more important to probe new physics beyond the SM, such as precision measurements, searching for dark matter and exotic phenomena.

Liquid-based detectors are widely used in particle and nuclear physics experiments, especially in intensity frontier for detecting rare signal events, due to its high cost efficiency in constructing large-sacle detectors. The well-known experiments include Super-Kamiokande detector [1], Sudbury Neutrino Observatory (SNO) [2], Kamioka Liquid Scintillator Anti-Neutrino Detector (Kamland) [3] and Jiangmen Underground Neutrino Observatory (JUNO) [5, 6, 7].

2. Detector geometry description

In liquid detectors, the conditions of the whole detector are preferred to be kept in a consistent status to minimize the liquid flows. However, keeping the uniformity of the liquid in the detector is difficult because liquid-based detectors for the next generation are designed to be more and more huge.

When liquid flows in the detector, its physical properties, such as refractive index and density, may change with the environment at different positions, which may introduce a deviation of the optical photon transportation in the medium from the ideal case, a uniform condition throughout the detector. The impact of such deviation on reconstruction of the physical signals also needs to be studied, especially to study the performance of detector in the large-scale experiments searching for rare signal events [8].

Geometry Description Markup Language (GDML) [9] is a popular extensible markup language designed for detector description in high energy physics experiments [10, 11, 12]. In the following sections, we will introduce how to exchange the geometry information for liquid detector with GDML and tessellated 3D detector modeling [13, 14], so that the dynamic geometry information can be shared between computational fluid dynamics (CFD) simulation and particle transportation simulation. Furthermore, some critical performance index of the detector after reconstruction, which are important for the physics goal of the experiments, can also be compared between the uniform and non-uniform detector.

3. The simulation and analysis framework

To study a non-uniform liquid detector, the key point is to provide the functionality to describe specific physics attributes for different parts of the detector. The whole detector is required to be divided into a grid structure to allow such description. And the more fine a detector is divided into, the more accurately the detector can be described.

So long as the way of detector division is consistent between the CFD simulation software and the detector simulation software such as Geant4, their physical attributes can be shared with GDML detector description. For example, the temperature difference of environment will affect density of the liquid, which drives the liquid to flow under pressure. While the density also affects the refraction and transparency of the liquid, which will change the transportation path of the photons, and finally affect the sensitive detector response to change the detector performance.

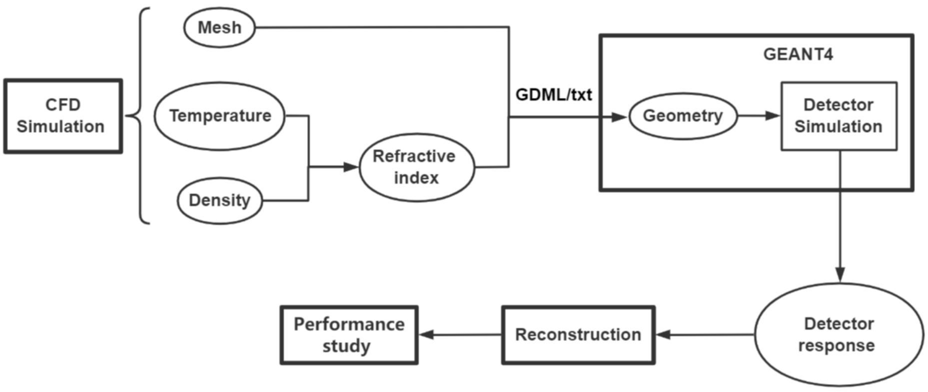

Figure 1. Architecture of the simulation framework and performance study.

The overview of the simulation and analysis framework is shown in Figure 1, which has the following steps:

1) The liquid flow is studied with a CFD simulation software with tessellated 3D modeling. The instant physical properties of the detector, such as temperature and density, is kept for refractive index calculation. The tessellated 3D geometry, as well as density and refractive index in each grid, is written out into file in GDML format.

2) The detector geometry in Geant4 simulation is constructed with the GDML file as input. The physical attributes saved in the GDML file is used to set the materials and optical properties in each part of the detector.

3) Detector simulation is conducted with the geometry initialized from GDML. The response of the detector, such as hit information, is exported for further event reconstruction and performance study.

4. Validation with toy model

We use a simple toy detector model, as shown in Figure 2, to validate the whole procedure and data flow in simulation. To avoid the impact from other optical processes, only the straight line propagation, Fresnel refraction and reflection of photons are allowed in the simulation, while all the other optical processes are turned off.

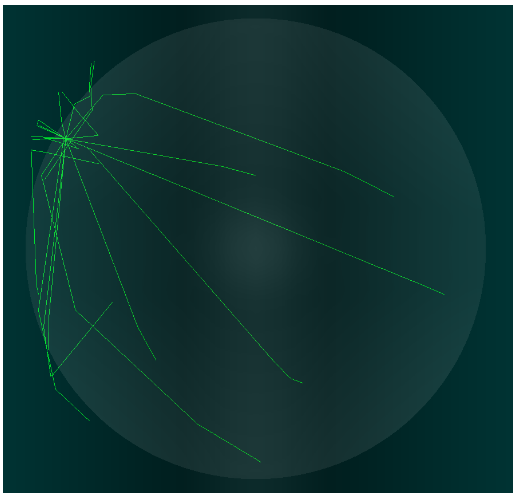

Figure 2. A toy model to illustrate the optical processes of photons while propagating in the media.

A sphere with the radius of 15 meter is constructed as a toy detector. For simplicity, the detector is filled with water. To better describe the water flow in CFD simulation, we divide the sphere into about ten thousand tetrahedrons. In this step, the flow of water is calculated using CFD simulation software COMSOL [15] with a meshed geometry. The refractive index of water is determined based on temperature and density.

In Geant4-based detector simulation, a virtual physics event is generated from a fixed vertex inside the sphere. Multiple photons are emitted from the event vertex. The photons propagate in the water detector in steps in Geant4 simulation. When the photons finally reach the surface of the sphere, they are assumed to hit the sensitive detectors deployed at the surface of the sphere and generate signal. The detector simulation exports the hit time and positions of the photons on the sphere surface after propagating through the water detector, and the signals will be used to reconstruct vertex of the event.

4.1. Liquid properties in COMSOL

Assuming that the temperature distribution in the spherical detector is non-uniform, the different densities of water will cause the water to flow. A fixed temperature difference of 35 K is set between the top and bottom side of the toy sphere detector as the boundary conditions. At the top and bottom regions, a constant heat flux is provided to simulate temperature difference from the exterior environment.

4.2. Study the deviation in Geant4

To compare the difference due to detector geometry non-uniformity, it is necessary to perform the Geant4 simulation twice. In the first simulation, the detector is constructed with a uniform medium to get the nominal simulation outputs. For comparison, a second simulation is performed using the same mesh partition of the detector, but initialize it with non-uniform medium from the above COMSOL simulation output. Meanwhile, all other detector conditions

Journal of Physics: Conference Series **2438** (2023) 012126 doi:10.1088/1742-6596/2438/1/012126

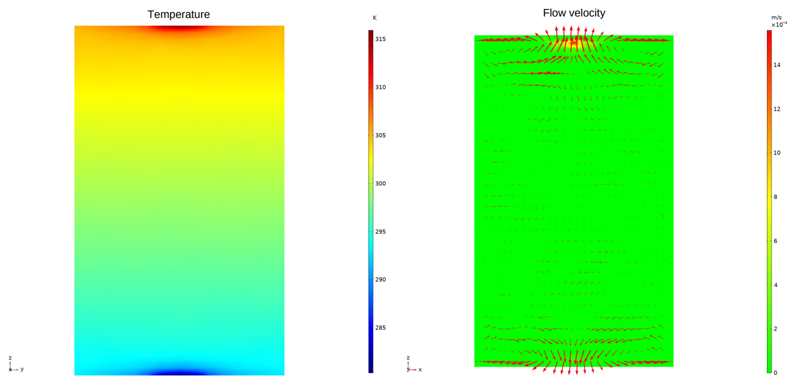

Figure 3. Projection of the fluid temperature and flow velocity in COMSOL simulation.

remain equal, including the event vertices and the number of photons emitted. Each event is simulated twice to get the deviation after Geant4 simulation. Figure 4 shows the difference of the photon hit positions on the detector surface, which is caused by refraction due to medium non-uniformity.

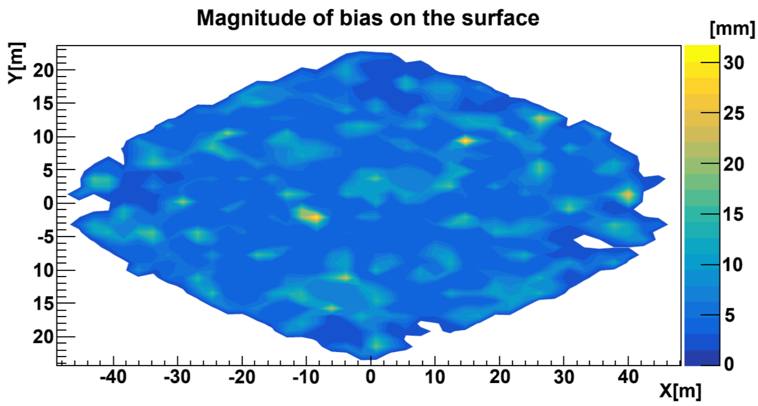

Figure 4. Comparison of the deviation of photon positions reaching the sphere surface in two Geant4 simulation cases, with uniform and non-uniform detector, respectively.

4.3. Study the deviation in reconstruction

Event reconstruction information, such as event vertex and event energy, are input for further physics analysis. Usually event vertex position reconstruction (showing where the physical events are generated) is one of the most important physical quantities to measure in many high energy physics experiments [16, 17]. And the vertex resolution, which is used to evaluate the deviation of the reconstructed vertex from its true position, is critical in many physics analyses and will finally affect the physics goal measurement of an experiment. Here we use a simple charge-weighted algorithm to reconstruct event vertex from positions of the photon hits responded and recorded on the sphere surface of the detector.

Figure 5 shows the distribution of reconstructed event vertex deviation from the output of ten thousand Geant4 simulated and reconstructed events. Most of the deviations are less than 10 mm, while the distribution has a long tail up to 80 mm. The two Geant4 simulation results are reconstructed with the same charge-weighted algorithm.

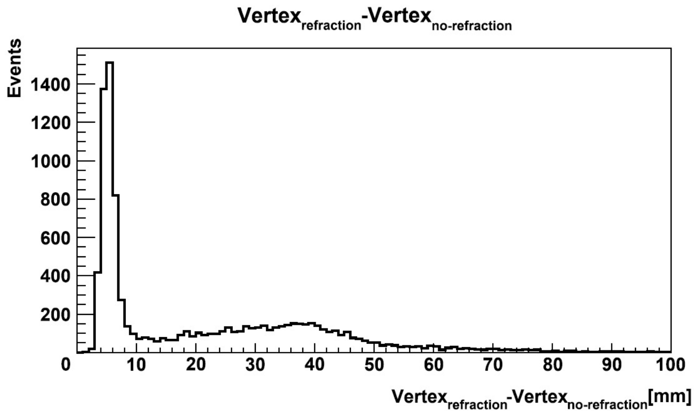

Figure 5. Comparison of the reconstructed vertices deviation due to geometry non-uniformity.

5. Conclusion and outlook

Liquid based detectors are widely used for neutrino and dark matter search experiments. The systematic uncertainties in simulation and reconstruction due to detector geometry non-uniformity is necessary to be evaluated, especially for large-scale detectors. We propose a novel method of sharing dynamic geometry between CFD and Geant4 simulation to study the deviation caused by detector non-uniformity, and validate its feasibility with a toy detector after simulation and reconstruction. It also has great potentials in detector design, visualization, outreach and other aspects of high energy phsyics experiments.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (No.11975021, 12175321, U1932101), the Strategic Priority Research Program of Chinese Academy of Sciences (XDA10010900).

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