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Accelerating TimeSPOT Detector Simulation with Deep Learning

The TimeSPOT project has developed innovative sensors optimized for precise space and time measurements of minimum-ionizing particles in high-radiation environments. These sensors demonstrate exceptional spatial resolution (around 10 μm) and time resolution (around 10 ps), while withstanding high fluences (> 10^{17} 1 MeV n_eq/cm^2). Tests on small-scale structures confirm their potential for deployment in next-generation inner trackers, including potential applications in experiments such as the new VELO detector of LHCb Upgrade II (Hi-Lumi LHC) and neutrino-tagging techniques. However, large-scale simulations within a full detector apparatus are essential to validate performance. Detailed simulations using Geant4/TCAD/TCoDe are computationally expensive, limiting design studies. To address this, we have developed a fast simulation based on deep learning, initially focusing on a Multi-Layer Perceptron (MLP) architecture. This work establishes a crucial proof-of-concept for applying machine learning to accelerate detector simulation.

Our approach involves training the MLP on a dataset of simulated TimeSPOT events (single-pixel geometry) generated with Geant4/TCAD/TCoDe. The trained model is converted to highly optimized C++ code via ONNX and ROOT TMVA SOFIE, and has been successfully integrated into the Gauss simulation framework. This integration demonstrates the feasibility of embedding machine learning models directly within complex simulation environments.

Results demonstrate a substantial speedup (10^4-10^5 times) compared to traditional simulations, while maintaining good accuracy. Subsequent work has explored advanced architectures, including Edge-Activated Adaptive Function Networks (EAAFNs), achieving even higher accuracy (R^2 > 0.99 for charge, R^2 > 0.93 for CoG). These EAAFN models are candidates for future integration.

This fast simulation, currently for a single TimeSPOT pixel, paves the way for significant advancements: multi-pixel geometries, entire detector modules, and other detector types. The proven methodology –training, conversion to optimized C++, and integration –can be extended to parameterizable simulations.

AI keywords

fast simulation; deep learning; MLP; EAAFN; SOFIE; ONNX; TimeSPOT; Gauss

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Track Classification: Simulations & Generative Models