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FPGA-Based Data Processing using High-Level Synthesis on the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (ADAPT)

FPGAs are widely deployed on high-energy astrophysics telescopes to read out sensor data from front-end electronics. To support continuous data streams or high trigger rates, FPGA logic may be employed to process raw sensor readout values, reducing the volume of data transmitted, processed, and stored by downstream CPU-based computational platforms. Traditionally, this logic is specified in a hardware description language (HDL) such as VHDL or Verilog. Across instruments, these FPGA-based processing pipelines often have similar semantics and share common stages. However, diverse telescope designs require unique implementations of the constituent algorithms, and the logic is often rewritten from scratch for a new instrument. Writing, simulating, and hardware debugging of HDL-based firmware is rarely straightforward and introduces significant overhead to the instrument development cycle. As an alternative, High-Level Synthesis (HLS) tools enable these algorithms to be implemented in a high-level language, such as C or C++, which eases modifications and enables fast prototyping and deployment. Nonetheless, writing performant HLS code is not straightforward, and requires an understanding of how the synthesis tools convert high-level language constructs, compiler-specific pragmas, and vendor-provided template libraries to hardware circuits.

This work presents an initial HLS library of common algorithms for deployment in particle astrophysics detectors. We apply it to the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (ADAPT), a prototype high-altitude balloon mission with an anticipated flight during the 2026-27 Antarctic season. ADAPT is an MeV-TeV gamma-ray instrument that combines a pair tracker and Compton telescope in a single monolithic design by using a combination of scintillating fiber trackers and CsI:Na tiles read out with wavelength shifting (WLS) fibers for imaging and edge-mounted SiPMs for calorimetry. Our library enables efficient processing of analog waveform data from ADAPT's >2000 sensor readout channels. Steps include per-channel preprocessing and filtering, including data acquisition, pedestal subtraction, photon counting (via peak detection, waveform integration, and gain correction), as well as cross-channel event building stages, including island detection and centroiding. With ADAPT, we demonstrate the several advantages of our library. It is *performant*, processing hundreds of thousands of event triggers per second. It is *lightweight*, enabling deployment on embedded FPGAs flying aboard the instrument. It is *flexible*, allowing easy modification to explore the trade off space between speed and resource utilization. And it is highly *extensible*, enabling straightforward swapping of algorithmic modules as simulations and lab tests reveal new processing and analysis requirements.

Collaboration(s)

APT

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