Innovations in Trigger and Data Acquisition systems for next generation physics facilities

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February 9, 2022

Abstract

Data-intensive physics facilities are increasingly reliant on massively heterogeneous and large-scale data processing and computational systems in order to collect, distribute, process, filter, and analyze the the ever increasing extreme volumes of data being collected. Moreover, these tasks are often performed in hard real-time or quasi real-time processing pipelines that place extreme constraints on various parameters and design choices for those systems. Consequently, a large number and variety of challenges are faced to design, construct, and operate such facilities. This is especially true at the energy and intensity frontiers of particle physics where bandwidths of raw data can exceed 100 Tb/s of heterogeneous, high-dimensional data sourced from >300M individual sensors. Data filtering and compression algorithms deployed at these facilities often operate at the level of 1 part in 10^5, and once executed, these algorithms drive the data curation process, further highlighting the critical roles that these systems have in the physics impact of those endeavors. This white paper aims to highlight the challenges that these facilities face and to identify a range of concepts and proposals for meeting these challenges with innovations in trigger and data acquisition devices and systems for next generation physics facilities.

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

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1 Introduction

We aim to summarize several of the "grand challenges" that we envision may or must be met by innovations in trigger and data acquisition (TDAQ) systems for next generation physics facilities. These challenges will then be discussed in the subsequent sections, with specific examples of existing or proposed solutions, drawing on the community letters of interest as well as current literature in the field.

- Designing, building, integrating, and operating large-scale, heterogeneous, and dynamic physics facilities for data acquisition, filtering, processing, and storage using both commodity and custom hardware, firmware, and software.
  - What are the particular challenges that we face that are niche or nonexistent in industrial applications? Exceptionally large numbers of devices/channels; data structures much more well-defined; temporal structures of the data; high-rate applications; high bandwidth requirements; data integrity and robustness; reproducibility
  - How can we take devices, firmware, and software designed by industry for industrial applications and build the systems we need to do physics with them? What innovations are needed to do this?
  - What is the current state of the art for heterogeneous digital and analog solutions? Dynamic and reconfigurable hardware? Deployment of advanced algorithms (AI/ML)? heterogeneous CPU/GPU/FPGA/SoC systems?
  - What innovations are being considered or needed for achieving this?

  - What physics selection and filtering algorithms and architectures can be deployed on these commodity systems? What are the advantages and potential physics impacts of that approach above and beyond the current state of the art?

- Pushing the envelope of industry standard devices and systems, and their intended goals, by confronting these commodity solutions with the specific and specialized needs of low-latency, high throughput and high performance physics facilities. Considering and exploring the paradigm shifting approaches that can take TDAQ systems to new levels, taking advantage of new technologies and opportunities in new ways.
  - What can the scientific world feed back into the industrial world in order to adapt technologies and/or create new ones that meet the goals and challenges of next generation physics facilities?
  - Further integration of AI engines into devices; wireless 5G command and control;
  - What innovations are being considered or needed for achieving this?
  - Explore clock-driven vs. event-driven approaches and innovations, synchronous vs. asynchronous trigger systems, and the traditional boundary between them
  - Where are we going with the next generation of high-level synthesis? Will the latency and resource requirements of applications for reconfigurable devices be able to be met by the optimization procedures of future HLS or HLS-like software/firmware? What will HLS be like in 20 years?
- Installation, integration, validation and operation of the developed systems
  - What foundational and operational skills and training do we need to be able to achieve the goals?
  - What are the interfaces to other areas, fields etc?
  - Acquisition of domain knowledge
  - Recruit talent to do the actual work
  - Expertise that we need to build
  - Connect to the design, building, and execution
  - Need pool of people who actually know about devices, etc.
  - Workforce development

2 Challenges faced by next generation physics facilities

- Challenges that we face:
  - Data Acquisition and Trigger Enhancements for Low-Energy Events in DUNE (LOI 185)
  - DAQ System for a Large-Volume CRES Experiment (Noah S. Oblath, LOI 186)
- Physics selection and filtering algorithms:

  - Triggering on charged particles using silicon pixel detectors (LOI 184)
  - Real-time adaptive deep-learning with embedded systems for discovery science (LOI 190)
  - Track-based Triggers for Exotic Signatures

3 Hyper-dimensional data acquisition and processing systems at scale

- DUNE / CRES LOIs
- Edge Computing Devices for Detectors Developed for Scientific Applications (LOI 251)
- Self-driving data trigger, filtering, and acquisition systems for high-throughput physics facilities (LOI 189)
- Asynchronous First Level Trigger Systems for Future Collider Experiments (Darin Acosta, LOI 187)

Examples of challenges and solutions for systems with a large number of channels.

3.1 Asynchronous First Level Trigger Systems

The challenges of distributing and synchronizing stable, low-jitter, high-frequency clocks over a very large distributed system comprised of thousands of optical links will increase to address the needs of the experiments at future colliders. Moreover, the precision of the timing to be maintained will reach the level of tens of picoseconds, and the number of channels and processing boards will greatly increase with the increasing granularity of the experiments. Rather than maintain a synchronous system for the full data path to reach a first level trigger decision, it is proposed to tag the data with a time marker only at the very front-end of the detector electronics and transmit and process the data subsequently asynchronously as is already done traditionally for the data acquisition and high-level triggers after this first level. Effectively, the event builder infrastructure moves to process data at the full rate from the detectors. Already some portions of the first level trigger systems at the LHC experiments run asynchronously: the optical data links connecting the boards comprising the trigger system, for example, do not run synchronously since the frequency of the data link operation does not always match a multiple of the machine frequency. Additionally, some experiments also have introduced a "time multiplexing" approach to serve a complete set of detector data from a particular beam crossing to an individual board of the first level trigger. This proposal just extends this time-multiplexing concept to a fully asynchronous event builder architecture.

Additional benefits of an asynchronous system include a blurring of the lines between the first level trigger, which typically runs in fast FPGAs, and the higher levels, which typically run on CPUs and now also GPUs. In some sense, a set of FPGA, GPU, and CPU processors can be used to execute a mix of traditionally very fast algorithms for the initial selection of data and more complex algorithms that typically take more time for the final selection.

A small-scale prototype of such an asynchronous trigger system for the formation of track from the data of several muon detectors was developed and tested in Ref. [1]. The front-end trigger electronics of three spare cathode-strip chambers (CSCs) of the CMS Endcap Muon system were upgraded to perform pattern recognition and bunch-crossing assignment from the anode data at an 80 MHz frequency. Trigger primitives from up to 3 chambers were transmitted via 10 Gb/s serial links to a newly designed track-finding processor, a PC plug-in card, that could generate the asynchronous trigger acceptance signal with a time marker that is sent back to front-end boards for data read-out.

4 Opportunities for heterogeneous and dynamic systems

- Mu2e-II LOIs: trigger-less TDAQ, TDAQ based on GPU co-processor, 2-level TDAQ system based on FPGA pre-filtering, 2-level TDAQ system based on FPGA pre-processing and trigger primitives
- FPGA based artificial intellifence inference in triggered detectors (LOI 191)

5 Building and retaining domain knowledge and technical expertise

- Coordination with Community Engagement Frontier, Topical Group CommF1: Applications & Industry
  - Bruhwiler et al, “Collaboration between industry and the HEP community“ LOI 66
  - Mase and Kikuchi, “Technology transfer from KEK to industry: What is needed to commercialize the technology developed in high energy“ LOI 24

6 Discussion

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7 Conclusions

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References

[1] A. Madorsky, D. Acosta and H. Patodia, *An asynchronous level-1 tracking trigger for future lhc detector upgrades*, in *2006 IEEE Nuclear Science Symposium Conference Record*, vol. 3, pp. 1415–1419, 2006, DOI.