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Slow control and data acquisition development in the Mu2e experiment

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The muon campus program at Fermilab includes the Mu2e experiment that will search for a charged-lepton flavor violating processes where a negative muon converts into an electron in the field of an aluminum nucleus, improving by four orders of magnitude the search sensitivity reached so far. Mu2e's Trigger and Data Acquisition System (TDAQ) uses *otsdaq* solution. Developed at Fermilab, *otsdaq* uses the *artdaq* DAQ framework and *art* analysis framework, for event transfer, filtering, and processing. *otsdaq* is an online DAQ software suite with a focus on flexibility and scalability, and provides a multi-user interface accessible through a web browser. A Detector Control System (DCS) for monitoring, controlling, alarming, and archiving has been developed using the Experimental Physics and Industrial Control System (EPICS) open source Platform. The DCS System has also been integrated into *otsdaq*, providing a GUI multi-user, web-based control, and monitoring dashboard.

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1. Introduction

Lepton Flavor Violation (LFV) has been observed in the neutral sector in neutrino oscillations but not in the charged sector. In the Standard Model (SM), the predicted branching fractions of Charged Lepton Flavor Violating (CLFV) processes are below 10^{-50}. The observation of CLFV would thus provide unambiguous evidence for the existence of New Physics beyond the SM. The Mu2e experiment at Fermilab will search for the coherent neutrinoless muon-to-electron-conversion in the field of an aluminum nucleus ($\mu^- + {}^{13}_{27}Al \rightarrow e^- + {}^{13}_{27}Al$) [1]. The expected Mu2e single event sensitivity (SES) is:

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N(A,Z) \rightarrow e^- N(A,Z))}{\Gamma(\mu^- N(A,Z) \rightarrow \nu_\mu N(A,Z-1)^*)} = 3 \times 10^{-17}. \tag{1}$$

The current world's best limit $R_{\mu e} < 7 \times 10^{-13}$ (on gold) is from the SINDRUM II experiment at Paul Scherrer Institut [2]. In addition to Mu2e, the COMET experiment in preparation at J-PARC has an expected SES of 3×10^{-15} for Phase-I and $O(10^{-17})$ for Phase-II (on aluminum) [3], while the DeeMe experiment, also in preparation at J-PARC, has an expected SES of 10^{-14} (on carbon) [4].

The Mu2e apparatus includes three superconducting solenoids:

1. The Production Solenoid, where the 8 GeV pulsed proton beam (period of 1.7 μs) hits the tungsten production target and produces mostly pions;

2. The Transport Solenoid, which serves as a decay "tunnel" for the pions and performs a charge and momentum selection, thus producing the low-momentum μ^- beam;

3. The Detector Solenoid, where muons are stopped in the aluminum stopping target, form muonic atoms, then decay to 105 MeV/c^2 electrons, which are detected by state-of-the-art detectors for tracking and energy reconstruction.

The Mu2e Trigger and Data Acquisition System (TDAQ) is a streaming system with a software-only trigger designed to satisfy the following requirements [5][6]: Provide efficiency better than 90% for the conversion electron signal; Keep the total trigger rate below a few kHz - equivalent to approximately 7 PB/year of total data rate; Keep the processing time below 5 ms/event. To achieve these goals and allow for a higher off-detector data rate, the Mu2e Data Acquisition System (DAQ) is based on a streaming readout. This means that all detector data are digitized, zero-suppressed in the front-end electronics and then transmitted off the detector to the DAQ. In this paper, we present the Mu2e Trigger and Data Acquisition System (TDAQ) and the integration with the Detector Control System (DCS) prototypes built at Fermilab's Feynman Computing Center.

2. The TDAQ System

The Mu2e Trigger and Data Acquisition System (TDAQ) provides the necessary infrastructure to collect digitized data from the tracker, calorimeter, cosmic ray veto and monitor the beam status. The TDAQ employs 36 dual-CPU servers to handle a total rate of 192,000 proton pulses per second and an average of 5,400 events per second per server. According to preliminary estimates, the detectors generate approximately 120 kB of zero-suppressed data per proton pulse for a resulting

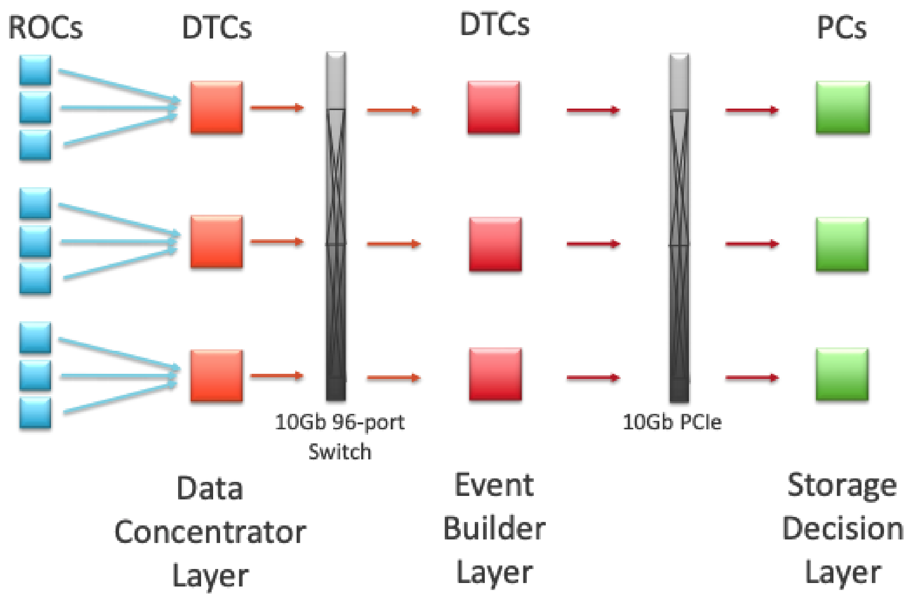

Figure 1: Mu2e TDAQ architecture.

average total data rate of about 20 GB/s when beam is present [5]. Figure 1 shows the global TDAQ architecture.

Each Read Out Controller (ROC) continuously streams out the zero-suppressed data collected between two proton pulses from the detectors to the DTCs (Data Transfer Controller). The data of a given time-frame are then collected in a single server using a 10 Gb/s switch. Then, the online reconstruction starts and a trigger decision is made. If an event gets triggered, the data from the cosmic ray veto (CRV) are pulled and aggregated into a single data stream. The DAQ servers filter these events (aggregator/data logger) and forward a small subset of them to the offline storage. A total of 497 ROCs and 83 DTCs will be used.

The TDAQ employes *otsdaq* as a software solution. Developed at Fermilab, it uses the *artdaq* [7, 8] and *art* [9] software as event filtering (data transfer, event building and event reconstruction) and processing frameworks. *otsdaq* includes a run control system using the data acquisition software XDAQ [10] implemented for the development and calibration-mode runs at CMS. The *otsdaq* development for Mu2e follows two main directions: server side and web side. The server side is developed in C++. The specific code for Mu2e is added through plugins (C++ classes inheriting from the appropriate base class). The web side (directly accessible to the end user through a web browser) is developed in HTML and JavaScript. Custom code for Mu2e is added in the form of web-apps through html files.

The Mu2e physics triggers identify signal event candidates [6]. It is implemented as a series of software filters applied after each step of track reconstruction. The total trigger rate is expected not to exceed 700 Hz [6]. With the *artdaq* framework, it is possible to limit the offline data storage to less than 7 PB/year with a reduction factor of about 100 at the event building level [11].

3. The Detector Control System

The Detector Control System (DCS) function is to monitor the detectors status and operational conditions. For each subsystem, the DCS allows to display real-time Graphical User Interfaces (GUIs) and archive the monitoring data to disk.

Mu2e selected EPICS (Experimental Physics and Industrial Control System) for the DCS slow control and monitoring software[12]. EPICS is an open source framework originally developed at Argonne and Fermilab and now used in numerous experiments [13]. An Input Output Controller (IOC), running for each subsystem on a central DAQ server, will provide channels for all data [14]. The total number of slow control quantities is expected to be of the order of thirty thousand. On average, these quantities will be updated approximately twice per minute, for a resulting generated data rate of 10 kB/s.

As part of the DCS, *otsdaq* delivers slow control data from the DTCs and ROCs to EPICS. The *otsdaq* allows the user to monitor and interact with the DAQ hardware and the other devices managed by EPICS to: Observe Process Variables (PVs) such as settings, alarms, warnings, readouts, timestamps, status; Interact through a web interface that is lightweight, user-friendly, ready to use, customizable; Implement custom handling of PV alarms integrated with the TDAQ state machine transitions.

The design of *otsdaq* involved C++ and web-app applications to include the Mu2e slow control monitoring, alarm handling, and TDAQ hardware and online daq slow control entities writing in EPICS.

4. Conclusions

In this article, we have presented the Trigger and Data Acquisition System (TDAQ) and Detector Control System (DCS) currently being developed for the Mu2e experiment at Fermilab. The TDAQ system uses the online DAQ software suite *otsdaq* developed at Fermilab to provide a high level of flexibility and scalability. The Detector Control System (DCS) system uses the open source framework EPICS developed at Argonne and Fermilab and widely employed in a number of experiments, including CMS. The *otsdaq* system includes a part of DCS that communicates with EPICS. A run control GUI has been developed and integrated in *otsdaq* to provide a multi-user, web-based control and monitoring dashboard.

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