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DESIGN AND IMPLEMENTATION OF AN INSTRUMENTATION & CONTROL SYSTEM FOR CATHODES AND RADIO-FREQUENCY INTERACTIONS IN EXTREMES (CARIE) PROJECT*

D. Rai†, T. Ramakrishnan±, W. Barkley, W.B. Haynes, E.I. Simakov, M. R. A. Zuboraj, T. Grumstrup, J.K. Quemuel, H.A. Watkins, Los Alamos National Laboratory, Los Alamos, USA
L. Graham, National Instruments, Austin, Texas, USA

Abstract

The Accelerator Operations and Technology (AOT) division at Los Alamos Neutron Science Center (LANSCE) is working on designing and implementing an Instrumentation and Controls System (ICS) for the Cathodes and Radio-frequency Interactions in Extremes (CARIE) project. The system will utilize open-source Experimental Physics and Industrial Control System (EPICS) developed for scientific facilities for control, monitoring, and data acquisition. The hardware form factors will include National Instrument's (NI) CompactRIO (cRIO) automation controller for industrial-like slow inputs/outputs and NI's PXIe (PCI eXtensions for Instrumentation Express) for high-speed data acquisition for diagnostic signals featuring masked and event-based time window capture. This paper discusses the reasons that led to the design, the hardware and software design specifics, the challenges that we faced during implementation, including the EPICS device support for NI PXIe, as well as the advantages and drawbacks of our system given the experimental nature of the CARIE project.

BACKGROUND

Particle accelerators are critical and established tools needed to meet national security and other essential exploration science. The demand for a more cost-effective X-ray source warranted the commissioning of a high gradient C-band (5.712GHz) accelerator development effort in the LANSCE accelerator facility at Los Alamos National Laboratory [1,2,3]. To enable multi-GeV proton radiography, LANL has suggested improving the LANSCE proton linac using a high gradient C-band [4,5]. The CARIE C-band high gradient photoinjector test facility is vital to developing a C-band accelerator to advance and enable that institutional capability expansion. The CARIE test facility will be instrumental in meeting and advancing institutional capability and future mission needs for advanced cathode and material studies [6].

To support CARIE project needs, the AOT-IC (Instrumentation and Controls) group was tasked with designing and implementing an integrated controls system to enable the operation of the accelerator facility. The facility required the capability to be accessed, monitored, and controlled through Central Control Room (CCR) by LANSCE's accelerator operators to enable 24/7 operation of the facility.

DESIGN APPROACH

Hardware Design Overview

To meet the design requirements for the CARIE accelerator facility, the hardware design for the control system involves three platforms as shown in Fig. 1:

1. NI 9048 cRIO
2. Soft IOC
3. NI PXIe

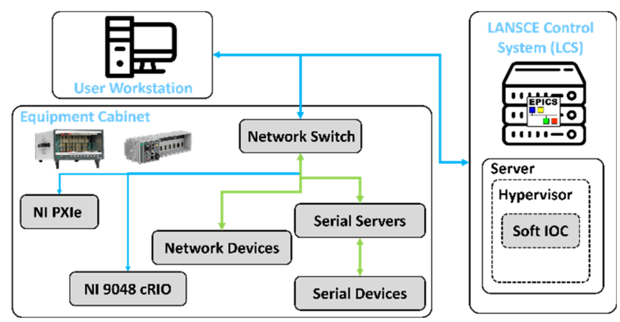

Figure 1: Hardware system design high-level overview

The first platform, the NI 9048 Controller Chassis, is a cornerstone of the LANSCE industrial control system. It is based on the NI cRIO platform, which have proven their reliability at the LANSCE accelerator facility. The NI 9048 controller chassis is equipped with all the necessary industrial control components for analog and digital input and output (I/O) control. It allows us to monitor, control, and optimize physical variables such as temperature, pressure, and flow rates. The multiple generations of successful cRIO control systems deployed in the facility make it an obvious choice, ensuring the project's needs are met without the need for significant modifications.

The second platform, the Soft IOC (Input/Output Controller), is a key player in the control system. It is designated for standalone system components that support ethernet/serial communication protocol for monitoring, controlling, and optimizing systems PVs. This includes various system components such as vacuum pump controllers, ion vacuum gauge controllers, and many other devices with ethernet or serial communication capability. The Soft IOC seamlessly integrates these components into the control system. Unlike typical physical hard-wired industrial I/O, the Soft IOC provides all the necessary PV information

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†drai@lanl.gov,
± tyagir@lanl.gov

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with a single cable connection to the EPICS control system via Ethernet or serial servers.

The third platform involves the NI PXIe form factor to enable high-speed data acquisition of forward and reflected waveform during RF (Radio Frequency) breakdown events from strategically located directional couplers in the accelerator. Understanding the breakdown events and their causes is critical for determining the maximum electrical field gradient that can be used safely in klystrons and accelerating structures [7]. The acquisition of breakdown pulses allows the characterization of breakdown effects such as field emission. Especially the timing of the breakdown pulses provides qualitative information about the nature of the breakdown, such as the location of breakdowns and quality of conditioning. Breakdown pulse timing, shape, and amplitude help distinguish whether the event is caused by inadequate system conditioning, field emission, or material deformities inside the accelerating structure. To process and capture the break-down event pulse waveform at a required accelerator repetition rate of 100Hz for pulse width from 400ns to 1us. PXIe-5775, FlexRIO Digitizer with two channels at 12-bit with 6.4GS/s and 6 GHz and NI PXIe-6674T Timing and Synchronization Module with Oven-Controlled Crystal Oscillator (OCXO) was selected to enable waveform capture. Apart from the NI PXIe platform fulfilling all the hardware requirements for the effort, their existing support relation with AOT-IC and available expertise in AOT-IC with the LabVIEW development environment played a significant role in our decision-making process.

Software Design Overview

The software development for the CARIE project is significant progress for LANSCE, showcasing our expertise in handling new and complex challenges. Our focus is on EPICS [8], a distributed controls architecture that can handle multiple data types and sample rates throughout the LCS. We have existing protocols to communicate with the cRIO and serial device hardware as shown in Fig. 2, through our extensive code base [9], introducing the PXIe for high-speed digitized data collection is a novel challenge. We are exploring multiple solutions to integrate this high-speed data acquisition into the EPICS environment at LANSCE.

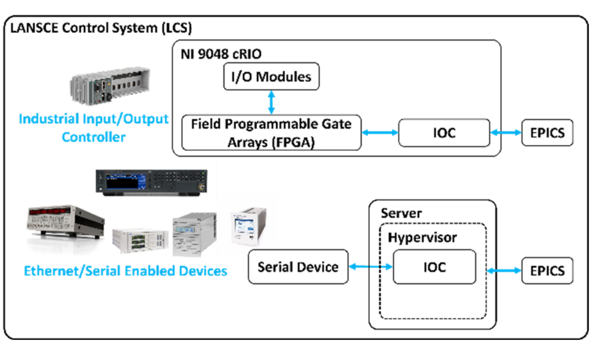

Figure 2: Industrial Controller Input/Output Control (IOC) and Soft IOC design high-level overview.

The PXIe software, written primarily in its native LabVIEW [10], is structured using the state machine framework [11]. This approach makes the code manageable and offers flexibility for future additions of software. The software utilizes a prebuilt reconfigurable FPGA module that can be set up with a trigger source for the digitizer. We have successfully implemented user-defined mask filters that are applied to incoming waveforms as shown in Fig. 3. These filters, which can be customized by the user, allow for more precise data collection by filtering out unwanted noise or signals. When a breakdown event is detected, i.e., the waveform breaching the mask, the program stores wave-form pulses before and after the breakdown event, as shown in Fig. 4. This feature is particularly useful for post-event analysis, as it allows users to capture the waveform data around the event, providing more comprehensive data for analysis. The user can set the number of pulses that need to be collected, and the resultant data is stored locally in a file with the current timestamp. Furthermore, the user can also set the sample rate if desired, showcasing the systems adaptability to user preferences. The current max sample rate for the PXIe is 3.2GS/s for dual channels and 6.4GS/s for single channels.

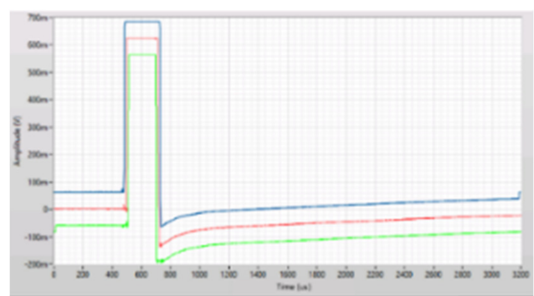

Figure 3: High speed data capture scheme LabVIEW Implementation (Red is the signal, Blue and green is user set upper and lower limit, respectively).

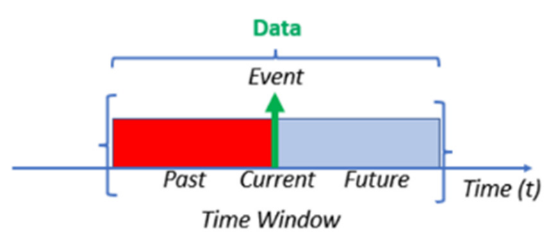

Figure 4: High speed data capture scheme with masking and event-based time window

Currently, two approaches are in progress to control the PXIe data and configurations using EPICS. The first approach uses LvPortDriver [12], a native C++ EPICS class that interfaces with LabVIEW and allows LabVIEW to transmit data using the asynPortDriver protocol. This approach requires the OS to be changed to Linux RT for efficient use. The native OS system for programming PXIe is Windows, which makes troubleshooting this form of code challenging for future development. However, we are making progress and are confident in our ability to overcome these challenges. The second approach is to establish a

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simple TCP/IP connection with a LabVIEW state machine integrated into the data acquisition code and have a Python client as the bridge between an EPICS soft IOC and the LabVIEW state machine.

CHALLENGES

Hardware

Establishing critical infrastructure, such as power and a network, for the project control system was a major challenge due to the age of the accelerator installation building.

Supply chain issues after the COVID-19 pandemic were a major issue worldwide, especially when procuring electronic components. The project was not immune to the issue and was impacted by the long lead time on critical system components, especially PXIe system components, delaying the development.

As the overall design for the accelerator matured, the requirements for the control system naturally evolved. This required us to occasionally reprioritize project tasks to accommodate these changes, which in turn led to some project delays. However, this adaptability is a testament to our team's flexibility and commitment to delivering a high-quality project.

Software

The PXIe software development is challenging since it is novel to the facility. Existing code base for the cRIO and ethernet/serial hardware, helps offset the research and development risks.

The LvPortDriver, has been successfully deployed for a few projects over the years [13,14] for cRIO development. However, LvPortDriver requires the PXIe OS to be converted to Linux RT, which is not the native LabVIEW programming environment. This approach requires high level of expertise for implementation due to its sparse usage.

Hence, we are also developing a TCP/IP protocol in which a LabVIEW server streams the high-speed data and a Python client that can stream the data and convert it into EPICS waveform PVs [15]. We already use Python to communicate with PVs using the pyepics package [16]. The disadvantage is that it is network-based, unlike LvPortDriver, which shares the EPICS IOC integrated with LabVIEW, but TCP/IP is straightforward and ubiquitous.

CONCLUSION

The project is progressing well and is expected to complete most of its major milestones by the end of fiscal year 2024. We have already established all the critical infrastructure for the facility and integrated vacuum system components into the EPICS control system for the Klystron condition process.

The control system project requirement is evolving as the overall accelerator design matures. We are diligently supporting the project needs, addressing challenges with robust safety and engineering approaches while incorporating project lessons learned.

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