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LANSCE CONTROL SYSTEM's 50th ANNIVERSARY*

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Abstract

After almost exactly 50 years in service, the LANSCE (Los Alamos Neutron Science Center) control system has achieved a major milestone – replacing its original and reliable RICE (Remote Instrumentation and Control Equipment) with a modern customized control system. The task of replacing RICE was challenging because of its technology (late 1960's), number of channels (>10,000), unique characteristics (all-modules data takes, timed/flavored data takes) and that it was designed as an integral part of the whole accelerator. We discuss the history, RICE integral architecture, upgrade efforts, and the new system providing cutting-edge capabilities. The boundary condition was that upgrades only could be implemented during the annual four-month accelerator maintenance outage. This led to a multi-phased project which turned out to be about an 11-year effort.

INTRODUCTION

In early June 1972, the world's most intense proton beam was delivered through nearly a mile of vacuum tanks at the new Los Alamos Meson Physics Facility (LAMPF), now known as the Los Alamos Neutron Science Center, or LANSCE. As the facility has evolved over five decades, proton beam is now delivered to five state-of-the-art experimental areas, a capability that makes the accelerator unique among its peers. LANSCE has embarked on improvements to ensure that the facility remains a leader for the coming decades. Across the accelerator, teams are replacing older systems with newer, more capable, and safer ones [1]. The control systems also underwent a major upgrade to keep up with technology maturation and the increasing demand for more data at a higher quality.

CONTR OL SYSTEM HISTORY

LAMPF, as LANSCE was called until the late 90's, was one of the first major accelerators to be designed in the 60's for computerized control [2]. All access to accelerator data was through a locally designed, centralized system with remote acquisition and control hardware called RICE. From the beginning the control system was in a continuous state of modifications. CAMAC devices were added to the system to complement RICE. By 1978 the control system provided access to approximately 4000 command-able devices and ~12,000 data points (~90% RICE & ~10% CAMAC). In the early 80's, the original System Engineering Laboratory SEL 840 control computer was not manufactured anymore, and a program started to replace it with a dual VAX 11/780 cluster. The cluster computers were continuously updated throughout the 80's and 90's. In the late 90's the controls group finished installing the cluster of five VAX 4000–96 workstations. In the early 1990's the controls group began integrating Experimental Physics and Industrial Control System (EPICS) into the LANSCE control system. During a control room upgrade new Sun workstations were introduced. These six-headed machines displayed the operator interface screens connected to EPICS applications and interfaced to the VAX-based applications through X-windows technology. As the years have passed, some additional channels were moved to VME but ~10,000 channels remained in RICE by the year 2000.

RICE INTEGRAL ARCHITECTURE

The RICE architecture was designed as an integral part of the LAMPF accelerator facility, with capabilities custom crafted to support controls and monitoring hardware in the accelerator. The initial description of the RICE hardware was given at the very first Particle Accelerator Conference in Washington, D.C., in 1965 [3] and more in-depth discussion in the context of the history of the LAMPF/LANSCE control system, see [4]. One most notable characteristic of RICE is that it is a star configured data acquisition system which supports control and beam synchronized type of data acquisition. At its heart, the RICE Interface Unit (RIU) was able to issue a parallel RICE module read request that provided a transverse snapshot of the accelerator. This implementation resembles the functionality of a timing system triggering gates to distributed data acquisition equipment.

- Timed data – scheduled data read with a micro-sec. granularity relative to the 8 milli-sec. timing cycle.
- Flavored data – scheduled data read on a beam pulse with specific beam parameters. Up to 96 parameters could be specified, including the desired beam species, the beam energy, and the beam-chopping pattern.
- All-modules data – data from all 72 RICE modules could be acquired with each read. Thus, a single request can read correlated data along the entire length of the linac in a one-microsecond window; 72 individual reads would otherwise be spread over 600 milliseconds. Thus, for instance, one could get a snapshot of all linac spill monitors on the same beam pulse.

UPGRADE EFFORTS

In the early 1990s and after 20 years in operation, LANSCE controls engineers determined that RICE had become an operational risk to the facility and its scientific mission. A proposal was made to rebuild the system in standard electronics, providing a complete duplication of RICE capabilities. Declining budgets and high cost, along with the undesirability of an extended accelerator downtime, prevented funding of this effort [5]. In the early 2000s

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a proposal was made to replace the industrial control channels with a commercial PLC system – a solution for replacing the time & flavored part of RICE did not exist at the time. The proposed solution would have replaced each slow control part of a RICE module with an Allen Bradley ControlLogix PLC. An EPICS Input-Output Controller (IOC) in a VME crate would have been used to control three to six PLCs in a geographical area; connection would be made via Ethernet, with an Ethernet switch used to isolate the IOC-to-PLC traffic from the rest of the network [5]. While a proof of principle was successfully tested in Module 48 in the 2003-2004 time frame this solution did not gain any traction due to its complexity and lack of funding.

As part of a planned LANSCE site wide upgrade project between Fiscal Year 2008 and 2014, the LANSCE Refurbishment Project (LANSCE-R) promised to provide the needed control system upgrade funding as part of a phased, multiyear project [6, 7]. However, the project was repackaged and re-emerged as LANSCE Risk Mitigation (L-RM) project of programmatic components and equipment directly related to the acceleration of the particle beam. Critical Decision 1 (CD-1) was obtained in November 2009 with a planned investment of ~$150M for the whole project - the control system was budgeted for about $30M. However, the FY10 funding legislation for Los Alamos National Laboratory (LANL) cancelled this line item and even future funding levels were uncertain and did not allow for the completion of the RICE upgrade scope when the project was declared done in 2015. To complete the original scope, efforts relied on operational and one time project funds. Given this financial uncertainty constant tactical and strategic planning combined with higher risk tolerance was required to successfully complete the retirement of RICE in 2022. Notable is that the project scope was mostly self-performed by LANL's Accelerator Operations and Technology - Instrumentation and Controls (AOT-IC) group.

CONTROL SYSTEM FORM FACTORS

After years of adding different hardware form factors, one of the design goals to replace RICE was to streamline and standardize the hardware form factors. After an analysis of alternatives two main systems emerged for a wide spectrum of instrumentation and controls applications [8].

(1) National Instruments' (NI) compact Remote Input Output (cRIO). NI provides a wide variety of modules that cover most of our needs. Beyond that third party products complement the NI module product line. A Module Development Kit (MDK) allows the development of custom modules. The cRIO is a fast and flexible solution with EPICS directly running on the Real Time Controller (RTC) which gives access to all the EPICS tools such as the sequencer, "bumpless reboot", and locally developed diagnostic and introspection utilities. The RTC embedded EPICS IOC communicates with a LabVIEW RT program via lvPortDriver or directly with the FPGA through NI's C-API. The whole system maximizes its flexibility through the freedom on how an application is partitioned between the FPGA, LabVIEW RTC, and EPICS database code. Another advantage is that the independently running FPGA, interfacing directly with the cRIO I/O modules keeps running even though the EPICS IOC is rebooted [4].

(2) The second system to replace RICE is a custom cPCI/VPX architecture in one crate. Its focus is beam-synchronized data acquisition. The cPCI side provides eight 6U cPCI slots for low cost per channel signal conditioning. One slot is usually reserved for a Micro Research Finland (MRF) Event Receiver for crate timing information. The VPX side modularizes on a new VITA standard high speed connector, with a switched PCI Express/Ethernet backplane fabric. The crate has six 3U VPX slots. It typically hosts up to five BittWare S43X FPGA DSP modules with an Altera Stratix IV embedding a NIOS soft-core based EPICS IOC running an RTEMS operating system (OS). For our design one slot is reserved for an PCI Express/Ethernet switch providing network connectivity to all VPX slots via the backplane. The dual (cPCI/VPX) architecture allows the communication between both sides via a PCI Express/Compact PCI Monarch communication bridge. The system is powered by three 250W, plug-in power supplies – the third one being used for redundancy.

UPGRADED SYSTEMS

Network Infrastructure

Between the 1980's and 2010, the LCS network had grown in a piecewise fashion leading to a network patch work. At its core, a 100 Megabit switch was connected to 10 Megabit edge switches. Few of them were managed which made the network management difficult. In 2011, a professionally performed network upgrade was the first L-RM scope element that was completed. It provided for the first-time network connectivity for the majority of the 800MeV linac. The newly installed fiber optics network has 10 Gigabit (Gb) at the core switches and 1 Gb at the edge switches. The network is built in a star configuration. In total, 451 fiber optic strands all originating near the Central Control Room were installed. Each of the 42 drop off locations has anywhere from 12 to 24 fiber strands. In total 12,800 feet of single mode fiber was installed throughout the accelerator facilities. At each primary drop off location a Nortel-5510/20 edge switch was installed. Near these switches 12 to 48 CAT6A twisted pair patch cords were run to secondary drop off locations. Under this regime 21,000 feet CAT6A twisted pair cable was installed.

BPPM and Delta-T System

As part of the L-RM project, in 2012 a process of replacing older Coupled-Cavity-Linac (CCL) Beam-Position Monitors (BPMs) with newer Beam Position and Phase Monitors (BPPMs) and their associated electronics and cable plants was started. In many locations, the older BPMs included a separate Delta-T loop for measuring the beam's central phase and energy. In total, 36 BPPM sensors were installed between 2012 and 2017. Subsequently, 28 cPCI/VPX instrumentation chassis were installed providing both beam position and beam phase data downstream of all CCL accelerating modules.

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Historically, the selection of amplitudes and phases of accelerating modules of the 805 MHz LANSCE linac were performed using a classical delta-t procedure. This turn-on method is based on measurement of difference in time of flights between 2 pairs of pickup loops when an accelerating module is off and on and comparing these differences with design differences. With the improvements of the 36 805 linac BPPM instrumentation (27 in support of the delta-t) the delta-t system is now capable of tuning modules in just a few minutes and provides direct phase and positions measurements that no longer rely on RICE.

Master Timer System

Essential to LANSCE's beam-synchronized beam operations is the timing system which underwent in 2014/15 a change from a centralized gate generating system to a distributed event-based system where timing gates are generated locally. The new Timing Pattern Generator (TPG) is a dual redundant system. Each TPG has a VME-64x crate, a MVME-6100 processor, a set of MRF event-generator modules, and a custom AC zero-crossing detector and beam-enable logic module implemented in cRIO. This FPGA-based beam enable logic has been used to implement specific features, such as enabling or disabling a beam from the operator consoles, single-shot mode, single-burst mode, continuous-burst mode, burst of bursts mode, and cycle stealing. The new TPG is still using the legacy coax cable-based distribution system through a legacy timing replicator until all Timing IOCs are deployed.

Wire Scanners

The cRIO platform has been also used to upgrade the aging Wire Scanner (WS) actuation and data acquisition system that has been using (1) RICE and (2) CAMAC technology. (1) A successful RICE replacement (L-RM) prototype was tested at the end of the 2010 run cycle which paved the way for a complete 32 WS system (actuator, cable plant, and instrumentation chassis) upgrade in the 805 MHz linac between 2011 and 2022. Each chassis is dedicated to one WS and has a Touch Panel Computer (TPC) to provide real-time visual display of wire-scanner operations and access to manual control of the WS actuator [8]. Furthermore, the project took advantage of the NI's MDK to design a specific, commercially unavailable, cRIO Analog Front End (AFE) module. The AFE is a dual channel, transimpedance amplifier with dual summed inputs and true DC coupling to collect the charge signals from the sense wires. (2) The 52 CAMAC based WSs have been upgraded using a dual chassis cRIO based solution. The a) Quad Actuator motion Controller (QAC) and b) Data Acquisition (DAQ) solution, both having a TPC, can run any type of stepper motor actuator at LANSCE (legacy L-RM, stripper foil, emittance, harp) while providing increased density/cost efficiency for stepper motor devices in congested areas (QAC operates up to four motors, DAQ expandable to 80 channels). Moreover, the system is open loop and closed loop compatible. In 2022, 52 WSs were upgraded to the QAC/DAQ solution - Line-D (9), MEB (15), in the REB (11), SY (9), and TR (8).

Non-Timed and Timed DAQ Systems

Industrial Controls To replace the slow monitoring & control functionality of RICE we chose the cRIO system because it is faster than PLCs (μsec vs. msec), allows hot swappable modules, and is easily configurable through its FPGA to match the behavior of RICE we were replacing. In 2011 we installed in Module 48 a unit as a proof of principle. Due to the length of the multi-year project (2011-2022) we have now two different cRIO controllers in use (cRIO-9024, VxWorks OS & cRIO-9038, NI's Linux Real-Time OS). In total we installed about 152 systems, that are mounted in a commercial BiRIO chassis which interfaces to BiRIO interface boards interfacing to field wiring.

Fast Data Acquisition To replace the timed & flavored capabilities of RICE we are using the cPCI/VPX system with its modular hardware components (FPGA Mezzanine Card) and industry standard modular interfaces. The so called TDAQ – timed data acquisition system shares most of its modular software and hardware components with our BPPM system and is therefore simplifying maintenance and spares inventory. Notable TDAQ logic-design specifics are a general-purpose waveform digitizer, CIC with FIR compensation down sampling low-pass filter producing additional precision, and FPGA accelerated piece-wise linear waveform element conversion. After ~3 years of installation work, in 2022 a total of 62 TDAQ systems were put into production interfacing equipment via a 16 channel Analog Front Interface (TAFI) conditioning board.

EPICS Software Changes To interface the new RICE replacement hardware with EPICS we preserved capabilities to view data selectively based on client application specified timing and flavoring parameters. This resulted in the EPICS/Channel Access (CA) Server upgrade so that logical configurations of beam gates, and the necessary timing parameters, could be specified when a client subscribes for process variable (PV) updates. EPICS IOC database and event-queue software also were upgraded allowing site specific companion data to be specified when posting signal updates from device support. Furthermore, it was necessary to add new sample-rate, default-filter, trigger-offset, timing gate delay-width metadata to EPICS that can be used to index waveform slices via the Lua subscription update filter. The changes were done in a generic backwards compatible way allowing the new data acquisition capabilities to be advantageous at any EPICS site, or not used depending on needs. For example, all LANSCE specific capabilities are integrated outside of the EPICS base distribution via Lua and C++ EPICS database configured snap-ins. Furthermore, the Lua language filter expression is specified as a channel name postfix and so all popular EPICS tools can access the new features unmodified.

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