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MODERNIZING THE SNS CONTROL SYSTEM*

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Abstract

The Spallation Neutron Source at Oak Ridge National Laboratory has been operating since 2006. An upgrade to double the machine power from 1.4 MW to 2.8 MW is currently underway and a project to add a second target station is in the preliminary design phase. While each project will add the controls needed for their specific scope, the existing control system hardware, software, and infrastructure require upgrades to maintain high availability and ensure the system will meet facility requirements into the future. While some systems have received new hardware due to obsolescence, much of the system is original apart from some maintenance and technology refresh. Software will also become obsolete and must be upgraded for sustainability. Further, requirements for system capacity can be expected to increase as more subsystems upgrade to smarter devices capable of higher data rates. This paper covers planned improvements to the integrated control system with a focus on reliability, sustainability, and future capability.

BACKGROUND

The Spallation Neutron Source (SNS) is an accelerator-based neutron facility that provides the world's most intense source of pulsed neutrons for research. The machine was originally commissioned in 2006 and began operating for users in 2007. The facility was constructed by a collaboration of six laboratories who delivered controls along with their systems. The SNS Controls Group was responsible for global systems, control system infrastructure and integration of the partner contributions to create a single Integrated Control System (ICS) [1]. Hardware and software standards were adopted for the control system including the selection of the Experimental Physics and Industrial Control System (EPICS) toolkit for control, communication, and operational services. Using EPICS then allowed a diverse set of hardware to be integrated into a cohesive system.

The client/server architecture of the SNS control system consists of three layers shown in Fig. 1. The front-end layer employs input/output controllers (IOCs) as servers to connect to devices in the field and execute run-time control functions. The communication layer passes data in the form of EPICS process variables (PVs) between front-end IOCs and client applications. The back-end layer uses workstations to execute client applications to provide operational interfaces and tools.

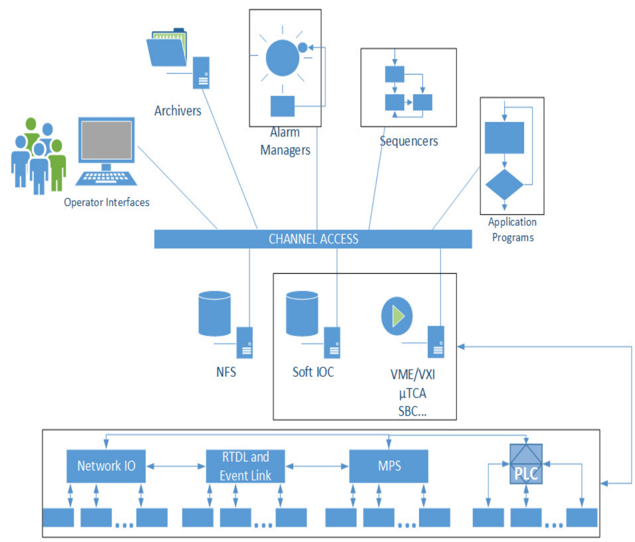

Figure 1: SNS ICS Architecture.

A key advantage of this type of architecture, where control functions, communications, and operational tools are decoupled, combined with the inherently distributed design of EPICS, is the ability to upgrade the layers, or individual components of a layer, independently thus providing a minimally disruptive path for upgrades which is essential for operating facilities.

The ICS, as originally constructed, employed commercial Linux servers and workstations for client layer and standard ethernet networking for communication. EPICS client applications providing operator interfaces included a custom alarm handler, the Extensible Display Manager (EDM) and the Channel Archiver. Several different types of IOCs were used, including VME/VXI Motorola single board computers running VxWorks, Allen Bradley Programmable Logic Controllers (PLCs) interfaced to Linux based (soft) IOCs or VME IOCs, and Windows PCs running Labview for Beam Instrumentation Devices. Table 1 shows the number of IOCs, PLCs, and EPICS PVs during initial operations and the present, pointing out where the system has expanded. While the number of VME IOCs has remained about the same, the number of soft IOCs has tripled supporting requests for new features as well as new devices and subsystems and the number of PVs has grown by ~50%.

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Table 1: ICS Growth

	2006	2021
VME IOCs	168	167
Linux IOCs	46	152
µTCA	0	9
Windows IOCs	248	170
PLCs	100	189
MPS inputs	923	1000
PVs	395000	603000

This combination of hardware and software, integrated using EPICS, provided a reliable control system, built on a foundation that could be extended by adding new IOCs and applications. However, it was recognized during early operations that improvements to the alarm handler would be necessary and some premature PLC hardware failures pointed to manufacturing defects that led to early upgrades of these processors. The availability history of the ICS is shown in Fig. 2. After an initial operations period where many problems were addressed with many systems, the original control system design and architecture are meeting the needs of the facility, however, many system components are aging and without upgrades, the ability to maintain high availability and support additional devices for new systems will be increasingly challenged.

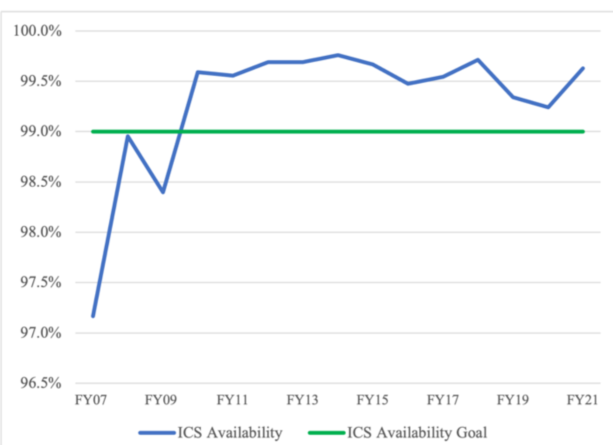

Figure 2: ICS Operational Availability.

LOOKING FORWARD

Over time, experience with the control system and performance analysis has informed planning for various upgrades. Predictably, hardware failure rates increase with years of operation and as parts become obsolete, the ability to repair failed hardware erodes. While not failing in the same way as hardware, software and firmware become compromised over time as vendors withdraw support for older versions or operating system upgrades are required, often to maintain an essential level of cyber security. Eventually, without upgrades, it becomes impossible to maintain platforms capable of compiling software or the tools needed to generate executable files creating an untenable situation for machine support and ruling out upgrades or any changes to system functionality. As smarter field devices are introduced due to upgrades of other systems the control system must also be prepared to support more modern hardware, often capable of higher data rates than original systems. The SNS also has two facility upgrade projects underway which will require additional control system capability.

The SNS facility has evolved since initial low power commissioning to run the full design beam power of 1.4 MW with > 90% availability. The initial suite of four instrument beamlines has been expanded to twenty and there are two construction projects underway that will expand the facility capabilities [2]. The Proton Power Upgrade project, scheduled to be completed in 2024, will increase the machine power from 1.4 MW to 2.8 MW by adding seven cryomodules in the Linac, replacing some Ring magnets and power supplies and upgrading the target design along with some elements of conventional and target utilities. The ICS will be extended to provide controls for the additional and upgraded systems.

The Second Target Station (STS), also in progress, will use the increased beam power to provide neutrons in an additional target station, initially with eight instrument beamlines and space for fourteen more. To create neutrons for the new target station, the 60 Hz proton beam will be shared between the existing target and the new one, typically by delivering 45 pulses to the first target station and 15 pulses to the second. The accelerator control system will be extended to new devices installed to create a new beam transport line. Further, the ability to provide independent operation of beam power to two destinations will require modifications to the timing system, machine protection system (MPS), kickers and the low-level RF (LLRF).

UPGRADES

Due to the flexibility and scalability of EPICS, upgrades can be pursued in parallel for the various control system layers and components while keeping the same underlying system architecture. While the primary motivation for most upgrades is to ensure the control system remains sustainable and capable of high availability operations and extensible such as is needed by the PPU project, the STS project will require a new capability to split the beam pulses between two destinations at different power levels.

Global Systems

The global systems in the SNS control system include the timing system, MPS and EPICS software along with the network and computing infrastructure. These systems can be complicated to upgrade due to their interaction with most devices on the controls network.

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Timing The timing system generates and distributes timing events as well as real-time data for each 60 Hz machine cycle to accelerator and instrument systems to synchronize system operations across the complex [3]. The original timing system, developed by partner labs, was based on the design and hardware of the existing Relativistic Heavy Ion Collider timing system at Brookhaven National Laboratory. The timing master was implemented using a collection of commercial and custom VME cards along with a complex real-time software application. The master communicated to a distributed network of fanout and receiver cards to deliver triggers and events.

While this system implementation performed the required functions, the installed hardware was relatively old technology and parts obsolescence became an issue after only a few years of operations [4]. Goals for an upgrade to this system included reducing the system complexity, improving availability and sustainability, and providing a phased upgrade path that would allow a gradual replacement of obsolete hardware without an extended machine outage period. Three custom boards were designed to replace a variety of VME boards, and the new design moved most of the previous software functionality into an FPGA. The new fan-out and timing receiver hardware was phased in during maintenance outages over several years and the timing master was commissioned and turned over to operations in October 2019. In addition to the original event and real-time data distribution based on twinaxial copper cabling, the new fan-outs also support a more convenient single-link fiber for newer timing receiver hardware. The firmware for the new timing system will be modified to provide the appropriate information, such as pulse destination, to hardware subsystems to support two beam operations for STS.

Machine Protection The machine protection system is designed to trip the beam within 20 μsec in the event an off normal condition is detected to prevent damage to the machine. This system is currently being upgraded due to sustainability issues with legacy hardware components that have reached end-of-life, and for which limited spares are available. The new design for this system utilizes commercial μTCA hardware with field replaceable units to reduce mean time to repair and minimize the number of custom interface components and therefore the probability of failure. The system consists of one master unit and ~64 field nodes connected to ~1000 devices which can signal the need to shut down the beam. The new MPS hardware has been installed and corresponding firmware and software have been developed to support witness testing during the run cycle in early 2022. For this test, the system will collect data without shutting down the machine, to verify it provides the same protection as the original system before the system is phased into machine operations. New MPS nodes for the PPU project will be built with the new MPS hardware.

EPICS The EPICS toolkit is used throughout the ICS to provide processing of control algorithms, communications, and operator interfaces. EPICS software is written and supported by a community of control system developers distributed across several national laboratories. The SNS started operations using EPICS 3.14.7. Various incremental updates have been applied over the years and the current operational version for most IOCs is EPICS 3.14.12.8. EPICS 3.14 is no longer being upgraded.

The EPICS Collaboration worked for nearly a decade to develop EPICS 4, to support a richer set of data types for more advanced devices and applications along with a new communication layer, PVAccess, to support higher bandwidth data transfers. Unfortunately, upgrading from and EPICS 3 system to EPICS 4 is virtually impossible for such a large operational EPICS installation due to the need to upgrade all devices and clients at the same time [5]. Recognizing that the modern features of EPICS 4 would only be available for new installations, the collaboration then produced a combined release, EPICS 7, which allows the simultaneous operation of EPICS 3 and EPICS 4 systems and both corresponding communication protocols within the same EPICS namespace [6]. This gives the ICS a viable upgrade path and work is underway to test EPICS 7 in our operational environment to ensure compatibility prior to widespread IOC and client upgrades.

After the SNS began operations, new operator tools were developed, primarily at the SNS, and shared throughout the EPICS collaboration [7]. These tools, packaged as Control System Studio (CS-Studio), include tools for archiving, data browsing, alarms, display building and graphical user interfaces and feature a common look, feel and behavior along with interoperability which was missing in the earlier tools which were each developed independently. These tools are now used in the SNS Central Control Room, and local control rooms, except for the new display manager for which the migration is in process but requires significant testing time due to the installed base of over 4,500 screens. Many of these screens are used as templates in specific applications or run custom scripts which complicates the conversion process. The new display manager tool is used throughout the SNS instrument beamlines which also have EPICS based control systems.

While software generally requires more frequent update cycles than hardware, this is especially true for graphical tools like operator interfaces. The original CS-Studio toolkit had to be refactored to remove its dependency on the aging Eclipse Rich Client Platform, which resulted in more efficient execution and a better development environment. These tools were adopted for the SNS instrument beamlines when they were upgraded to use EPICS and a new tool, Scan Server, was added for experiment setup and control. In parallel to the CS-Studio desktop version for control room usage, a web display version has been developed. While it is read-only and not meant to support the full feature set of the desktop version, it provides control system and beam line experts with very convenient remote access.

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Infrastructure The computing and network infrastructure of the control system benefits from on-going technology refresh. At least 10% and up to 25% of the network switches, servers and workstations are replaced each year to keep the equipment within the expected lifetime limits.

In addition to the in-place upgrade of network equipment, the overall network layout would benefit from a certain level of redesign. The original SNS ICS network was based on several VLANs. Over time, all VLANs have been merged into one large broadcast domain that EPICS servers and clients use to interconnect. The latency of the large domain has reached the point where network clients regularly need to broadcast several search requests before they see a reply. A redesign which for example separates the different types of network traffic and thus isolates the EPICS communication will be necessary before extending the existing network to cover many additional devices.

The servers and workstations are currently undergoing a major revision of the underlying operating system to 64-bit Linux as hardware is no longer available to run the older 32-bit versions. This requires recompiling the substantial installed base of server hosted software and extensive testing with machine operators to ensure functionality is maintained while this upgrade to a supported version of Linux is implemented. The advent of EPICS 7 is another motivation for developing a different network topology to fully benefit from the more efficient higher data transfer rate which should be expected from newer devices.

Along with the Linux upgrade, the software development environment is being restructured and the original CVS code management system is being replaced by Git, a more modern tool with a richer code management feature set. These changes will make software development, which may require multiple branches, easier to manage and merge into a final product for release. It will also simplify the process of installing different software versions.

Slow Controls

Industrial process controls solutions are used on the device control level for the many machine systems which do not require real-time functionality. These include the superconducting cryomodules, cryogenics plant, target facility, vacuum, and conventional facilities. Many of the PLC processors used in these systems were upgraded in 2009 following failures that were tied to manufacturing issues. While these systems have proven reliable, most of our installed base is at or near end-of-life when spares and firmware patches will no longer be available, leaving these systems vulnerable especially to security issues. Additionally, the underlying network technology (ControlNet, DeviceNet) exposes weaknesses that can be rectified by upgrading to the more modern Ethernet solution. In some cases, the segmentation of these systems, either by design or growth, is not ideal. Hosting multiple unrelated applications on a single processor expands the consequences of a single failure therefore these systems will be segregated. The future upgrade path includes new processors and I/O modules to run supportable firmware and reduce the probability of hardware failure during operations.

To minimize disruption, PLCs upgrades will be packaged to install new hardware and replace ControlNet or DeviceNet communication with Ethernet at the same time. Multiple PLCs are typically grouped into ControlNet clusters and all PLCs and communication modules in a cluster will be upgraded at the same time to avoid rescheduling ControlNet multiple times and the extra effort otherwise needed to reprogram and test the PLCs for each change. DeviceNet upgrades may prove more challenging due to the communication module being embedded in vendor supplied equipment. The small number of PLCs which host multiple unrelated applications will be prioritized for upgrades first. Due to resource availability, this work will most like follow the substantial completion of PPU controls in 2023.

Real-time Systems

The control system applications that require performance beyond that possible using industrial process controls technology were originally built using VME hardware and the VxWorks operating system. The original Motorola 2100 model processors lacked the required performance for some applications, most notably the LLRF. This model also suffers from poor network stack performance and is particularly vulnerable to reconnection failures. These processors are being replaced with the 5500 model which successfully addresses both issues. An upgraded VxWorks kernel is available to support the new hardware and fix the network stack issues. About 70% of the original processors have been replaced so far.

Some of these high-performance systems, built on VME or custom technology, have started to experience obsolescence issues and we have developed a common µTCA based approach to upgrade these systems. The concept was initially proven on the Ring LLRF which was originally very different from the Linac LLRF and suffered from early obsolescence and sustainability issues. The new Linac LLRF system being developed for PPU follows the µTCA model along with the new MPS and recent upgrades for the high-performance waveform generation and monitoring systems. Originally developed for the high energy physics community, µTCA provides a commercially available open-standard architecture with built in high availability options such as redundant power supplies and cooling. With a variety of commercially available modules and features to support high speed applications, µTCA is increasingly selected for new accelerator real-time systems providing an opportunity for collaboration. The nine systems installed so far have proven reliable.

Personnel Protection Systems

The SNS Personnel Protection Systems (PPS) are credited engineered controls designed to prevent people from harm due to hazards associated with operating the accelerator such as radiation and oxygen deficient environments. This is primarily achieved by providing access controls and interlocks linked to the machine status and monitoring

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radiation and oxygen levels. In the case of unexpected, elevated radiation levels, the machine is shut down and the source investigated. In the case of depleted oxygen levels, alarming beacons are activated triggering an area evacuation and investigation.

These systems were originally engineered using the same industrial controls technology discussed in the Slow Controls section of this paper but deployed on isolated networks and with additional processes in place for the development and testing of credited systems. These systems are being updated to use more recently available safety rated PLCs and I/O and Ethernet based communication modules. The PPS for at least one machine sector is upgraded each year. Recently, these upgrades have been combined with the requirement to provide additional PPS I/O for the PPU project. The radiation monitors are obsolete and will be replaced with commercial units and a low maintenance ODH sensor design is underway.

CONCLUSION

The three-tier architecture and distributed nature of the SNS EPICS based ICS has proven reliable for the first fifteen years of SNS operations. As the systems age, hardware and software can be upgraded with new designs in a minimally disruptive manner, during scheduled machine outages, by evolving layers and components individually or in groups. EPICS 7 provides a viable upgrade path for the run-time execution engine and communications layer. The configurable nature of the operational tools allows new displays to be created and added during operations and new alarm and archive parameters can be added by inserting an entry in a database even during machine operations. While this architecture is serving the facility well, it is clear many systems require technology updates in the coming years due to obsolescence.

While PLCs and IOCs can be replaced without changes to the underlying system, significant engineering effort in the form of design, documentation and testing is required to provide reliable replacement systems therefore the upgrade efforts will be paced by resource availability and should be considered an ongoing effort. With careful prioritization and adequate resource investment, procurement and labor, the ICS can evolve and serve the SNS well into the future. Confidence in this architecture and technical implementation is evidenced by the selection of EPICS for upgrades to the SNS instrument beamlines and the design of the control system for the STS which leverages the same EPICS based architecture of the original SNS ICS. Key to the success of the SNS ICS has been the free exchange of software and cooperative development efforts which are the hallmark of the EPICS Collaboration.

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Sincere thanks to the countless engineers, designers and technicians who have designed, built, maintained, and upgraded the SNS control system over the last twenty years and to EPICS developers everywhere who not only share their code, but also generously contribute their time and share their experience help others solve problems. The fingerprints on the SNS ICS come not only from SNS staff, but from the partner laboratories and other EPICS sites. The many exceptional individuals working together has truly made an unlikely collaboration work beyond what could have been imagined when EPICS was born over 32 years ago.

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