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CONTINUOUS MODERNIZATION OF CONTROL SYSTEMS FOR RESEARCH FACILITIES

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Abstract

The Spallation Neutron Source at Oak Ridge National Laboratory has been in operation since 2006. In order to achieve high operating reliability and availability as mandated by the sponsor, all systems participating in the production of neutrons need to be maintained to the highest achievable standard. This includes the SNS integrated control system, comprising of specialized hardware and software, as well as computing and networking infrastructure. While machine upgrades are extending the control system with new and modern components, the established part of control system requires continuous modernization efforts due to hardware obsolescence, limited lifetime of electronic components, and software updates that can break backwards compatibility. This article discusses challenges of sustaining control system operations through decades of facility lifecycle, and presents a methodology used at SNS for continuous control system improvements that was developed by analyzing operational data and experience.

INTRODUCTION

The Spallation Neutron Source (SNS) is a neutron scattering research facility with the world's most powerful pulsed neutron source. The facility started operation in 2006 and is currently undergoing a major Proton Power Upgrade (PPU) that will increase beam power from 1.4MW to 2.8MW when fully commissioned. The SNS Controls Integration group is responsible for global systems and control system infrastructure to form an Integrated Control System (ICS) for the SNS accelerator and target complex. The ICS has been largely successful at supporting SNS operations since initial commissioning and has played a key role of achieving overall SNS beam availability of over 90 %.

To achieve a sustained high availability, continuous maintenance and modernization efforts are required for all components of the ICS. The SNS Controls Integration group is performing regular activities during the scheduled maintenance periods. These include ensuring controlled temperature environment by cleaning or replacing air filters and fans for increased air flow through the electrical circuits, tracking inventory operational time and replacing components at about 80 % expected lifetime as provided by vendor or based on data collected at SNS, maintaining a healthy amount of fully functional spares with at least 10 % based on the number of installed components and in some cases much higher when components are becoming obsolete.

The preventive maintenance activities help reduce unexpected failures and allow for overall high availability. But the expected SNS facility lifetime is several more decades, and these activities are not addressing issues like electronics and software obsolescence, technological advances, increased demand for data, or functionality upgrades. The rest of the document will describe these challenges in detail and present modernization efforts by the SNS Controls Integration group to address them.

HIGH AVAILABILITY OF COMPUTING AND NETWORKING INFRASTRUCTURE

The computing and networking infrastructure are an essential part of every control system. Networking allows devices to be connected into one integrated control system and is the carrier of all the controls information including delivering alarms in a timely manner, reliably transporting archive data from source to data storage, and providing real-time monitoring and control of any aspect of the system. Computing is needed to host various applications for automation, data acquisition, diagnostics, operator tools and many others. Performance and throughput requirements are usually low for the control system environment and are certainly within reach of modern technology. But recent advances in technologies allow improvements towards reliability of these systems.

Originally the SNS ICS network infrastructure was divided in 3 logical layers as depicted in Fig. 1. The top layer consisted of a single network node called the network core switch. Its job is to define the network topology and route the traffic between segments as well as to connect to an external network through a firewall. Next down is a distribution layer whose role is to provide enough links to connect all end-point network switches on the next layer. End-point network switches' responsibility is to connect network devices to the network. With about 3,000 network devices and about 600,000 sensors and actuators on the SNS ICS network, neither throughput nor latency are a challenge for our 1 Gbps network. However, availability of every network switch and general network health are of the

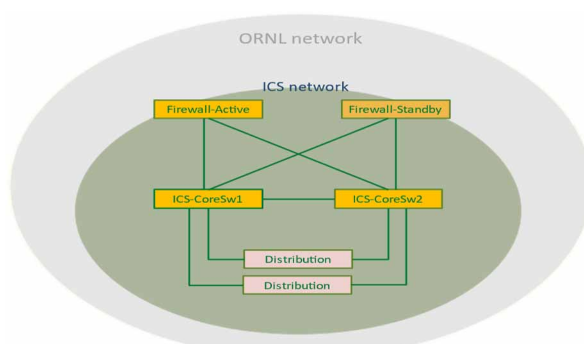

Figure 1: Complete redundancy and isolation of the SNS network for Integrated Control System allows high availability even when complete separation might be needed.

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utmost importance as they may cause confined as well as widespread control system unavailability, and in turn shutting down the accelerator. Particularly because of the heavy utilization of broadcast UDP packets generated by the Experimental Physics and Industrial Control System (EPICS) framework. EPICS is a distributed environment and uses broadcast UDP packets to search for process variables (PVs) when clients are looking to connect to Input/Output Controllers (IOCs). When a section of the network becomes unavailable, the existing connections are dropped and clients start searching for PVs from the affected areas, which may lead to overloading IOCs and causing them to stop communicating.

To provide the highest network availability possible, SNS has started to expand on network redundancy where feasible. This include adding second optical fibers, standardizing on dual power supplies with the second power supply connected to UPS power, combining redundant devices in a single virtual unit with an active-active failover mechanism that transparently transitions traffic away from the failed unit, and completely rebuilds part of the network that covers the data center with a full-mesh redundancy and increased speed to 4x25Gbps. In addition, monitoring of broadcast traffic through EPICS is already in place with ongoing efforts to provide complete network health monitoring in EPICS. Having extensive network monitors will allow engineers to see early signs of potential problems, and to use network health archived data in correlation with other incidents.

The computing resources at SNS are divided into two categories and are generally following the client/server architecture described in [1]. The high-availability servers are rack-mounted in a dedicated server room with restricted access and provide services essential for autonomous operation which includes all network services like DNS, NFS, authentication, logging; data storage for hosting software repositories, deployed applications, configuration files and user interfaces; and CPU resources for running control system applications. Generally, each of these services are hosted on a dedicated physical server to reduce the impact in case of a single failure, but this comes at increased maintenance cost. SNS has recently installed a virtual cluster consisting of 3 physical hosts interconnected with 25 Gbps Ethernet network and a new 120 TB storage appliance attached with Fiber Channel to the virtual cluster. Data centers around the world are using virtualization to reduce the operational cost, provide flexibility to adjust resources like CPU, memory and storage, and separate services for security provisions. In control system environments the biggest benefit of virtualizing services is the high availability guarantee that is achieved with an active mirroring of the entire system state and seamless transition to another host in case of a single failure. Another feature of virtualization that SNS is taking advantage of is the hardware independence, that allows us to continue supporting 32-bit operating systems where software cannot be ported to 64-bit architecture.

Client workstations provide visual interfaces to the control system and are in control rooms and throughout the facility for convenient access to control system functions. Aside from their generic Linux operating system, they carry no control system configuration and can be easily replaced if they fail prematurely.

CONTINUOUS SOFTWARE UPDATES

The SNS ICS is a heavily interconnected environment in terms of physical links between devices, but there are even more logical connections that mesh functional blocks into one coherent control system. The network binding these systems together is typically isolated or even air-gapped from the rest of the internet to minimize the potential unintentional or deliberate interference from outside. However, strict separation doesn't necessarily mean that no software updates or patches should be done after systems have been tested for proper operation and commissioned in the production environment.

During design and development of a new research facility, projects tend to keep upgrading externally provided software to latest versions when available. Towards the end of the projects, these versions get frozen to prevent inadvertent errors during deployment. Afterwards, software upgrades become an operational responsibility and often do not receive enough attention when they operate as designed. But a control system in a research facility is an organic entity and tends to grow over time to support new experiments, facility upgrades and expansions. EPICS with its modular design is very capable of expanding the control system functionality, but additional EPICS servers or clients can change the dynamics in the communications behavior, and they can significantly affect existing systems. With recent PPU upgrades at SNS, the increased broadcast traffic used by EPICS for finding sensors has caused existing EPICS IOCs to sporadically seize communicating. Investigation revealed that the combination of over 10 years old EPICS and VxWorks operating system supporting most of the IOCs is susceptible to communication issues in the broadcast-heavy network environment. Recent versions of EPICS and VxWorks tend to fix this issue, but the effort required to adapt SNS specific applications to the newest versions of EPICS is significant. In response to this discovery, SNS Controls Integration group has adopted a policy for regular upgrades for EPICS-based software. The first step is to bring all existing systems to newer versions of EPICS and all support modules, which includes moving some IOCs from a VxWorks platform to soft IOCs or Linux based MicroTCA. Afterwards the upgrades of any software supporting the IOCs should be updated about once a year during the maintenance periods. It is estimated that the combined effort required for regular upgrades in the next 10 years will be less than the effort required to do major upgrade and validation every 10 years.

The initial SNS Control System implementation developed many new software applications and tools to support SNS operations. These included EPICS modules like the genSub record for processing waveform data in C functions and EtherIP [2] for PLC communication, custom alarm handling solutions based on EPICS records, visualization tools and operator scripts for automation. Many of

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these products have been made available to the EPICS community and have been maintained and improved over the years by SNS staff and the community. But some of the custom tools remained installed and used only at SNS. Such tools tend to be more difficult to maintain long term as the original authors take new responsibilities. The SNS Integrated Controls group has been actively replacing this site specific software with more generic alternatives when available. Examples of recent upgrades at SNS include complete transition from custom records-based alarm handling to the EPICS standard CS-Studio BEAST and moving EDM screen files to a common location for better compatibility with WebEDM and WebOPI solutions.

In addition to control system updates that are driven by various upgrade projects mentioned so far, the SNS Controls Integration group has been actively adding capabilities for monitoring various aspects of the control system health with the intent to further increase control system and machine reliability. Two projects are currently underway with completion expected in early 2024. To troubleshoot network communication issues largely due to the EPICS broadcast traffic, a network monitoring-based EPICS SNMP Device Support Module by NSCL/FRIB is being employed to monitor network parameters like traffic utilization, signal strength and general equipment health information. With transition from VME systems to MicroTCA platform planned to complete in the next 5 to 8 years, monitoring MicroTCA systems is becoming essential. The MicroTCA smart platform provides a plethora of hardware related sensors to monitor using IPMI protocol. In addition, assets and deployment information like model/serial numbers, installation date, slot information is available for every component of MicroTCA system down to fans and power supplies and can be efficiently used for scheduling preventive maintenance activities. Epicsipmi [3], an EPICS module developed at SNS also allows remote rebooting of an entire MicroTCA or individual components for authorized operators only.

HARDWARE UPGRADE CYCLE

Like many other research institutes, SNS is also facing challenges surrounding specialized and often custom electronics hardware. These challenges include components lifetime, parts obsolescence, and technology advancements. When SNS was built, many of the electronics applications for communication and interfacing with other systems were built with custom Printed Circuit Board (PCB) designs and integrated in a Versa Module Europa (VME) platform. A few examples include fast Machine Protection System, Power Supply Controllers, Timing System for synchronization and real-time data distribution. Many of these custom applications now have obsolete parts and at the minimum the PCB design needs to be updated.

In some cases, the impact of obsolete components is significant and requires a complete PCB redesign. Combined with some other shortcomings of our previously used VME platform, SNS has chosen a MicroTCA platform for new higher performance designs. The migration from VME to MicroTCA will be gradual and is mostly driven by the expected lifetime of the existing electronics. Employing off-the-shelf components where feasible is highly encouraged in all new applications. With the use of generic FPGA carrier boards and FPGA Mezzanine Card (FMC) extensions, custom PCB designs are much simplified. Most of SNS hardware engineering expertise has thus shifted towards development of digital firmware designs. Generic and reusable firmware IP blocks have been developed to allow faster implementation of specific applications. Examples of these reusable IP blocks include a PCIe module for communication with CPU, CrossBar [4] for inter-blade communication, and the SNS timing receiver module. With these building blocks implemented, the firmware development of specialized applications can be streamlined which significantly reduces time from design to deployment. Using this approach, several systems have already been successfully migrated to the MicroTCA platform, including the Injection Kicker Waveform Generator and Injection Kicker Waveform Monitor. The Low-Level RF redesign was required by the Proton Power Upgrade project and was migrated to the MicroTCA platform as well. New LLRF systems needed for PPU have been deployed, with the intent to replace all existing VME-based LLRF systems with MicroTCA LLRF in the future. The Machine Protection System (MPS) was facing hardware 15-year lifetime limits (Fig. 2) and components obsolescence challenges. The redesigned MPS is based on MicroTCA platform and uses standardized Aurora protocol for real-time low-latency communication with field nodes to satisfy the main requirement to stop the production of a beam in under 20 us after a beam misalignment has been detected. The new MPS implementation is complete and is currently being deployed for production in early 2024. Given the number of specific VME applications remaining, it is expected that full transition to MicroTCA at SNS will happen in the next 5 to 10 years.

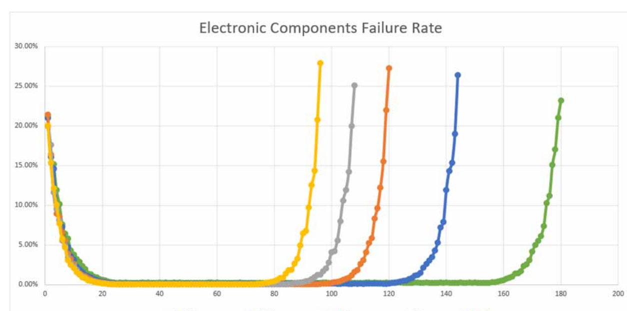

Figure 2: Electronic equipment is tested before installed and is replaced at about 80% expected lifetime to avoid the tail of the bathtub curve.

CONCLUSION

A control system supporting a research facility plays a critical role for facility operations and reliability. Only a properly designed and implemented system can deliver on these expectations and new projects are allocating around 5% of total budget for the control system purposes to ensure the new research facility can be efficiently and reliably operated once completed. After the momentum of a new

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project, the control system must continue to operate reliably for the entire lifetime of the facility. During decades of operation, the control system must be able to adapt to new technologies, extend the functionality, and sustain the increased amounts of operational data and sensors. It is essential that sufficient effort and focus is dedicated towards continuous updates of all control system components, not only to meet high availability expectations but also to maintain the technological edge needed for any upgrades. Continuous updates in smaller steps also ensure gradual adoption of new technologies, and further avoid disruptive impact of equipment and software becoming obsolete or reaching end of the supported lifetime.

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