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EPICS ARCHITECTURE FOR NEUTRON INSTRUMENT CONTROL AT THE EUROPEAN SPALLATION SOURCE

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Abstract

The European Spallation Source ERIC (ESS) are currently developing a suite of fifteen neutron instruments, the first eight of which will be available for routine scientific use by 2023. The instrument conventional control system will be distributed through three layers: local controllers for individual instrument components; Experimental Physics and Industrial Control System (EPICS) software to implement higher level logic and act as a hardware abstraction layer; and a high-level experiment control program, which has an executive role, interacting with instrument components via the EPICS layer. ESS are now actively designing and prototyping the EPICS controls architecture for the neutron instruments, including systems which interface to core instrument components such as motion control systems, neutron detector readout systems, sample environment equipment, neutron choppers, instrument Programmable Logic Controller (PLC) systems, and the interfaces to the NICOSII experiment control program. Systems engineering methodologies are being applied through the control system development lifecycle to provide traceability. Prototyping activities have been executed in an integrated and coordinated manner to demonstrate the EPICS controls architecture in an environment representative of the neutron instruments to which the architecture will ultimately be applied.

INTRODUCTION

The European Spallation Source (ESS) European Research Infrastructure Consortium (ERIC) is an ambitious project to build the world's most brilliant neutron source near Lund, Sweden.

A total of 22 neutron research instruments are planned, with development of 15 of those currently funded and underway. In addition, the ESS Test Beamline will be developed to characterise the neutronic properties of the neutron source (spallation target and moderator) prior to the scientific instruments being available. At least eight of the instruments will be ready for routine scientific use by 2023.

The ESS accelerator, spallation target and neutron instrument suite are being developed in partnership with research facilities across participating countries, which enables the project to capitalise on existing European experience in these technological domains. This distributed nature of the construction project also presents challenges in terms of ensuring consistency in the architecture and composition of the deliverables to ESS. This has important long term ramifications, such as affecting recurring maintenance costs.

In order to maximise consistency of the neutron instrument controls, the following high-level architectural and organisational interfaces have been established:

- Personnel Safety System: The PSS is a safety system responsible for mitigating against radiation, oxygen depletion and other safety hazards stemming from fixed equipment on each instrument. The PSS is developed to the IEC 61508 functional safety standard and is an independent system outside the scope of the conventional controls discussed here.
- Neutron Instrument Technologies: ESS staff are working with partners to define standard components and interfaces, such as defining a standard motion controller, control interface to all ESS neutron chopper systems and a readout and control system for the neutron detectors.
- Integrated Control System: ESS has adopted the Experimental Physics and Industrial Control System (EPICS) framework to interact with individual hardware components, including lower level controllers. The ICS Division also define and develop standard hardware platforms for control system use.
- Data Management and Software Centre: The DMSC are responsible for the acquisition and analysis of the scientific data from the ESS instruments. This layer also includes the NICOSII experiment control program, which includes a graphical user interface (GUI) and a scripting environment for executing neutron science experiments.

The work described in this paper relates principally to the Integrated Control System (ICS) layer of the instrument controls architecture, including interfaces to the other layers. In the following sections, the systems engineering strategy will be described, then the major infrastructure components used by ICS, then the control system strategy for major classes of instrument component and finally some ongoing activities to demonstrate and refine the controls will be detailed.

SYSTEMS ENGINEERING

Due to the magnitude and particular challenges of developing the controls for the ESS instrument suite, ICS have adopted a mix of formal and informal processes to efficiently engage the individual instrument projects.

Developing an early synoptic view and preliminary overall design of the control system for each instrument is important, and this is where a flexible and iterative methodology has proven useful. Control system staff at

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similar neutron facilities provided feedback that they found an informal development process to be most effective. This is partly due to the nature of designing a complex research machine, like a modern neutron instrument, where the individual components can themselves be major engineering development projects. These are typically developed with an initially high degree of technical uncertainty, which is gradually decreased during the development. This occurs in iterative refinements of the neutron instrument's design itself, and in conjunction with increasingly detailed knowledge of other enabling systems.

To realise this in a practical sense, the first contact between ICS and the instrument projects involved several meetings to identify each component of the (as-planned) instrument which has a controls interface. Special use-cases, which may present particular constraints during the control system design, are also identified. This information is captured informally on a 'wiki' so that each stakeholder can work to maintain the information.

The subsequent control system development stage is to formulate a Systems Engineering Management Plan (SEMP) for each instrument project. This identifies, still at the level of the entire instrument, the control system design lifecycle, scheduled reviews and necessary documentation. The SEMP needs to be formally approved by management within ICS as well as the instrument stakeholders.

The top-level requirements of the control system, mostly at the level of only identifying sub-systems which need to be controlled, are then captured in a System Requirements Specification. While detailed, technical and testable requirements are initially sparse at this high level, the SRS document requires formal review and approval by control system experts and process owners.

Approval of the SRS allows a Preliminary Design Document to be developed for the instrument control system. This identifies a high-level architecture for how the controls of individual sub-systems will be implemented and identifies the control system hardware that will be required for the instrument. The information in this document is necessary for planning the timeline and budget for the control system development, while also informing the instrument project about the controls architecture for that project.

For the individual instrument sub-systems a more sequential systems engineering methodology is applied. The life cycle model used for the controls integration of instrument components specifies a) system life cycle stages, b) reviews that mark the transitions from one stage to the next, and c) the applicable technical documentation conventions.

INFRASTRUCTURE AND WORKFLOWS

The Integrated Control System at ESS includes standard workflows and infrastructure for developing and deploying control software, for the instruments as well as other facility components such as the accelerator. Some of these major elements of the overall architecture are briefly described below.

Timing System

ESS have elected to use a distributed, delay-compensated timing system produced by Micro-Research Finland. This system provides the signals required to synchronise the operation of the entire facility, from the proton source at one end, through to the neutron detectors at the other.

The timing system is particularly relevant for instrument components that require precise synchronisation, such as rotation of neutron chopper systems, some motion axes, neutron beam monitors and the neutron detectors. The timing system can be used to provide digital strobe and clock signals to external components and also to trigger interrupt-driven software activities.

ESS EPICS Environment

The ESS EPICS Environment (EEE) is a build and deployment system for EPICS modules used at ESS. During development of EPICS modules, the EEE significantly reduces boilerplate by providing a single, general Makefile which inspects the project and manages the build, cross-compiling for several architectures and EPICS versions. EEE also simplifies dependency specification by allowing users to list required modules in the IOC startup script. These dependencies are then dynamically loaded at runtime. This capability allows users to switch between versions of modules and even versions of EPICS without recompilation.

As a deployment tool, EEE presents a synchronised repository of EPICS modules across ESS and its in-kind partners using NFS or rsync. A continuous integration server triggers automatic builds whenever a tagged release is pushed to the Git repository of an ESS module. These releases are then deployed as numbered module versions within EEE and available for use in IOCs on any synched computer. The EEE can also use the NFS file system deploy IOC startup scripts to specific hosts. In this scheme, control computers find IOC scripts using their host name and start the appropriate IOCs automatically at boot time.

Controls Configuration Database

The Controls Configuration Database (CCDB) is a tool designed to help manage information about physical and logical devices at the ESS. Within this database, device types, properties, tags, units, and relationships can be specified.

In practical terms, CCDB is used to model the relationships between control system components used at ESS. Reusable models of controls software can be created and then customized to represent individual deployments. At a high level, models might include information about software dependencies and device model numbers. At the instance level, CCDB models describe, among other things, the physical computers on which a piece of control

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software is to run and which specific pieces of equipment it is controlling. Several other ICS tools, such as IOC Factory, can consume this data to help automate common configuration and deployment tasks.

IOC Factory

The IOC Factory is a tool used to manage EPICs Input Output Controllers (IOCs) at ESS. It provides a workflow for configuring, generating, browsing, and auditing IOCs. With IOC factory, users can generate an IOC for a particular device tree within the CCDB and provide the specific environment variables, macro definitions (such as IP addresses for the devices to be controlled), etc. required by that IOC at run-time. IOC Factory can then generate the required startup script and deploy it to the appropriate server through EEE. Users may also browse a database of existing and historical IOCs and their metadata and track changes to the IOCs monitored by the system.

Channel Finder

Channel Finder is a directory service for EPICS PVs. It can be combined with the Recsync library to allow IOCs to automatically upload a list of their Process Variables (PVs) to the Channel Finder on startup. The Recsync library will also notify Channel Finder when those PVs are available. PVs can also be tagged with metadata in the form of key-value pairs. The Channel Finder will be used to support plug and play for sample environment equipment at ESS instruments. Users can also use Channel Finder aware software like Control System Studio to browse available PVs. This solves one of the major shortcomings with EPICS, which is the lack of a PV discovery mechanism.

EPICS Archiver Appliance

The EPICS Archiver Appliance was developed at SLAC as an extension of existing archiver software. It's job is to continuously record the values of EPICS PVs. An archive of historical values is valuable for observing trends, validating data, and troubleshooting problems at the facility.

The EPICS Archiver Appliance presents a graphical web interface as well as an HTTP API for configuring and interacting with the archive. Historical trends are easily visualized in software like Control System Studio, or can be queried via HTTP if more detailed analysis is required. The Archiver Appliance also supports data retention and decimation policies to help manage the stored values.

CS-Studio

Control System Studio (CSS) is a GUI designed to help users interact with EPICS and related software. It includes tools for building operator interfaces to devices exposed over EPICS as well as the ability to display historical data from the EPICS Archiver Appliance. It can also communicate with Channel Finder to help users browse available PVs.

At ESS, all engineering screens for the instruments will be implemented as CSS operator interfaces. These screens will contain low level information for expert control of ESS equipment. This is not to be confused with the NICOSII experiment control program which will present the primary controls interface to science users of the neutron instruments.

INSTRUMENT COMPONENTS

A central component of the controls strategy for the ESS instruments is to define standard modular solutions for control of common hardware components. These solutions will be applied to all instruments, where possible, even though the individual instrument projects are being undertaken by different partner institutions throughout Europe. The following sections outline some key points of the control system used for each of these major groups of instrument components.

Motion Control

Motion axes are a common component of neutron instruments. These include, for example, slit systems used to control the size and divergence of the neutron beam, and shutters used to block neutrons and other radiation when the instrument is not actively acquiring data.

Motion systems for the ESS instruments will be implemented using a standardised digital Motion Control Unit (MCU), with the possible exception of a small number of systems with special constraints. In addition, the ESS Motion Control and Automation Group have created a catalogue of standard motion actuators and other hardware components to assist in achieving a level of homogeneity across the instrument suite.

In many cases individual motion axes can be exposed by the MCU, and up through the EPICS layer, in a generic way. The logical implementation of any higher-level functionality (for instance, treating four motion axes as a slit system having virtual axes for the aperture position and size) can be implemented in the NICOSII experiment control program layer in these cases.

For other motion systems the logical implementation of device-specific functionality will be implemented in the MCU or in the EPICS layer, exposing a higher level interface to NICOSII. A typical case where this design choice is appropriate is when there are machine protection issues, such as the chance of collision between two motion stages. Implementing the logic, including collision-avoidance functionality, at the lowest level is a more robust design where such hazards exist. Another use-case for implementing functionality at lower levels is where systems need to respond to feedback rapidly.

Most motion stages will operate asynchronously, however some systems will require mechanical motion systems to be synchronised with the 14Hz pulses of neutrons. In this case the timing system will be used to precisely synchronise the clock of the MCU.

Neutron Chopper Systems

Neutron choppers are mechanical systems, typically rotating discs coated in a neutron absorbing material, with windows for permitting neutrons at particular phase

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angles of the disc. These can be used to create a time structure in the neutrons arriving at the sample or to select only neutrons of particular energy ranges, based on the time of flight to the chopper from the neutron source. The fastest ESS choppers will operate at speeds approaching 400Hz.

ESS will have a large number of choppers from different manufacturers which need to be controlled. To accommodate this diversity and provide a common interface from the chopper systems up to the EPICS layer, the ESS Neutron Chopper Group have a developed a local controller called the CHopper Integrated Controller (CHIC).

Control information will flow from the experiment control program, through the ICS EPICS layer, to the CHIC and then to the chopper drive controller using the appropriate protocols for the particular chopper drive.

The ICS EPICS layer will also configure the local timing system according to the requested chopper parameters. The timing system will deliver digital phasing references pulses to each chopper drive, at the frequency and phase offset (with respect to the accelerator) specified by the experiment control program. The timing system will also capture a timestamp for every rotation of each chopper, which will be published via EPICS from where it can be consumed by the data reduction software.

In addition to the control and timing of the choppers, the EPICS layer will also interface with a Conditioning Monitoring System for each chopper system. This will monitor conditions such as vibration and hardware temperatures, providing valuable engineering information and early warning of potential failures.

Neutron Detectors and Beam Monitors

Neutron detectors are used to measure the temporal and spacial distribution of neutrons that have been scattered from the sample under investigation. Ultimately data analysis software can use this data to constrain properties of the sample.

Beam monitors are generally low efficiency neutron detectors which can be used to quantify the characteristics of the neutron beam at a particular point on the instrument. They are used, for instance, during commissioning of neutron chopper systems and also to allow data normalisation based on the inter-pulse and intra-pulse variability from the accelerator and spallation target.

To minimise the diversity of readout systems on the ESS instruments, the ESS Detector Group are developing a standard readout system which will be able to interoperate with a range of analog front-ends and detector technologies. This will minimise long term costs for the facility while also helping to standardise the interface between the detectors and the event formation software being developed by DMSC which will ingest the raw data from the detectors.

The Detector Group, ICS and DMSC have been working jointly to prototype the readout system, which includes EPICS control and an interface to the centralised timing system.

Other components of the detector systems, such as high voltage power supplies, also need to be integrated with the control system. In general these will be implemented using commercial solutions. ICS have implemented EPICS controls for two manufacturers that will be suggested to the instrument teams.

Sample Environment Systems

Sample Environment Systems (SES) are used to regulate the physical conditions that the samples of interest are being studied are exposed to during the experiment. Typical SES may regulate the temperature, humidity, pressure or magnetic field, for instance. Some ESS instruments will have specialised SES mainly used on only one instrument, however most instruments will also rely on SES from an ESS 'pool' of such devices, on an experiment-by-experiment basis.

Unlike the other components described, where a level of homogeneity is a goal, ESS will have a high diversity of SES items that will be used on the instruments. These each require integration with the control system. Ultimately such equipment needs to be controlled from the experiment control program, via the EPICS layer, and status information from the SES needs to be monitored so sample conditions can be aggregated with neutron data for analysis.

One of the strategies that ESS have adopted is that most SES will have a local computer that physically moves with the rest of the equipment. This computer will run the EPICS software to communicate with the SES components. The computer will also allow the SES to identify itself, through a mechanism using the EPICS Channel Finder, so that the NICOSII experiment control program can automatically notify the scientific user which SES are currently available on a particular instrument.

Instrument PLC

Programmable Logic Controllers (PLCs) are standard solutions for process control. ESS have a framework agreement to use a particular model of PLC throughout the control system, so the PLC and selection of input/output modules will be well standardised.

PLCs will be used on the neutron instruments for control and monitoring of the vacuum systems, monitoring the supply of utilities (such as cooling water temperature or compressed air pressure) to each instrument and possibly for monitoring the flow and other properties of gas supply to the neutron detector systems.

PROTOTYPING ACTIVITIES

ESSIIP

The ESS Instrument Integration Project (ESSIIP) is a development project to prototype and integrate the controls of major components of the instrument controls

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architecture. Accommodated in an ESS laboratory, this project facilitates not just the development of controls for individual system components (e.g., neutron choppers), but also provides the first complete vertical controls stack from the NICOSII experiment control program, through the ICS EPICS layer (including the workflows and infrastructure outlined previously), and finally to the local controller level of the individual instrument components.

ESSIIP has proven to a very successful tool for developing the instrument controls. Deploying the controls for individual components in a comprehensive, integrated and coordinated manner served as a catalyst to facilitate the development of additional aspects of the final architecture. This strategy also provided a common goal for many internal groups within ESS which ensured that good workflows, communication and a common understanding of the controls architecture was agreed very early, from the perspective of the overall ESS project.

HZB V20 Neutron Instrument

Following from ESSIIP, ESS have approved the use of the V20 neutron instrument at the BER-II reactor, operated by Helmholtz-Zentrum Berlin (HZB), for use as a controls integration platform. Access to this will enable control system elements for the ESS instruments to be further developed, commissioned and improved in advance of the time that a working control system is required at ESS.

At the time of writing, the DMSC have deployed NICOSII as the experiment control program on V20 and ICS have deployed EPICS infrastructure and a timing system on this instrument. Future integration activities will include demonstrating the principal controls components of an ESS instrument, including motion axes, neutron choppers, detector readout and data aggregation in a coordinated way at a working neutron science facility. This will help to ensure the full breadth of controls system components are able to deliver when they are needed for the ESS instrument suite.

CONCLUSION

ESS are building the world's most brilliant neutron facility, which will eventually include at least 22 scientific instruments. Due to the challenges of developing the controls for these instruments, a systems engineering strategy is being utilised and high level software infrastructure provides a basis of the control system architecture. ESS are investing effort to reduce the inhomogeneity of the instrument hardware and control systems, especially for common components found on most instruments. In order to ensure the control system has reached a demonstrated level of maturity prior to the commissioning of the first instruments at ESS, the control system is being prototyped in an integrated way, both in a laboratory setting and on an existing neutron instrument at a partner facility.