THE LARGE SCALE EUROPEAN XFEL CONTROL SYSTEM: OVERVIEW AND STATUS OF THE COMMISSIONING

A. Aghababyan, R. Bacher, P. Bartkiewicz, T. Boeckmann, T. Bruns, M. R. Clausen, T. Delfs, P. Duval, L. Froehlich, W. Gerhardt, C. Gindler, J. Hatje, O. Hensler, J. M. Jäger, R. Kammering, S. Karstensen, H. Keller, V. Kocharyan, O. Korth, A. Labudda, T. Limberg, S. Meykopff, M. Moeller, J. Penning, A. Petrosyan, G. Petrosyan, L. Petrosyan, V. Petrosyan, P. Pototzki, K. Rehlich, S. Rettig-Labusga, H. Rickens, G. Schlesselmann, B. Schoeneburg, E. Sombrowski, M. Staack, C. Stechmann, J. Szczesny, M. Walla, J. Wilgen, T. Wilksen, H.-G. Wu, DESY, Hamburg, Germany
S. Abeghyan, A. Beckmann, D. Boukhelef, N. Coppola, S. G. Esenov, B. Fernandes, P. Gessler, G. Giambartolomei, S. Hauf, B. C. Heisen, S. Karabekyan, M. Kumar, L. Maia, A. Parenti, A. Silenzi, H. Sotoudi Namin, J. Szuba, M. Teichmann, J. Tolkiehn, K. Weger, J. Wiggins, K. Wrona, M. Yakopov, C. Youngman, European XFEL GmbH, Hamburg, Germany

Abstract

The European XFEL is a 3.4 km long X-ray Free Electron Laser in the final construction and commissioning phase in Hamburg. It will produce 27000 bunches per second at 17.5 GeV. Early 2015 a first electron beam was produced in the RF-photo-injector and the commissioning of consecutive sections will follow during this and next year. The huge number and variety of devices for the accelerator, beam line, experiment, cryogenic and facility systems pose a challenging control task. Multiple systems, including industrial solutions, must be interfaced to each other. The large number of bunches requires a tight time synchronization (down to picoseconds) and high performance data acquisition systems. Fast feedbacks from front-ends, the DAQs and online analysis system with a seamless integration of controls are essential for the accelerator and the initially 6 experimental end stations. It turns out that the European XFEL will be the first installation exceeding 2500 FPGA components in the MicroTCA form factor and will run one of the largest PROFIBUS networks. Many subsystem prototypes are already successfully in operation. An overview and status of the XFEL control system will be given.

INTRODUCTION

The European XFEL is a 3.4 km long X-ray Free Electron Laser (4th-generation light source) located in Hamburg, Germany. Its linear accelerator is based on superconducting RF-technology delivering 2700 electron bunches at energies of 10.5 GeV, 14 GeV, or 17.5 GeV with a bunch train repetition rate of 10 Hz. The undulator systems of the facility will produce spatially coherent photon pulses which are less than 80 fs long showing a peak brilliance of 10^{32}–10^{34} photons/s/mm^2/mrad^2/0.1% BW in the energy range from 0.26 to 29.2 at beam energies of 10.5 GeV, 14 GeV, or 17.5 GeV. Installation work in the accelerator and beam line sections is progressing. Technical commissioning and set-up with beam will be performed in stages in 2015 and 2016. First lasing should be possible end of 2016.

The control system of the European XFEL is an effort of various distinct groups at DESY and the European XFEL GmbH. This paper describes the concepts and features of the individual solutions for accelerator, undulator, photon beam line, and cryogenic and utility controls. It addresses the challenges to be faced, discusses the interoperability between the systems and reports on the status of the whole controls project.

ACCELERATOR CONTROLS

The accelerator control system provides an environment to supervise, control, synchronize and protect the technical equipment of the accelerator. It includes among other things a large scale front-end electronics infrastructure based on the novel MTCA.4 standard [1], a timing system, a machine protection system, server software and driver libraries, communication protocols, a finite-state machine tool to facilitate process automation, and a design tool for graphical user applications. In addition, it provides a central Data Acquisition System (DAQ) aggregating and storing shot-synchronized, bunch-resolved data from distributed sources and supporting various software-based feedback systems. The environment is completed by a code repository, a repository to keep the configuration data for generating graphical user panels, various Web services, and common IT infrastructure.

Conceptual Design

Primarily the conceptual design of the accelerator control system follows the DOOCS control system ansatz in place at the FLASH facility, itself a quasi-template for the European XFEL. DOOCS-based controls cover all aspects of equipment dealing with bunch-synchronous fast data taking and algorithms. In addition, slow control such as vacuum or magnet controls is also handled by TINE-compliant control system components. TINE is the principal control system of the PETRAIII complex (3rd-generation light source). Both DOOCS and TINE are full-featured control systems and have been recently tuned to interoperate seamlessly [2].

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System Components

More than 200 MTCA crates distributed along the accelerator host electronic plug-in modules with more than 2500 FPGAs executing tasks such as beam current read-out or low-level RF-measurements and control algorithms. Universal Linux drivers with hot-plug support are used as an interface to low-level DOOCS servers which provide board conifguration and basic read-out. Data are distributed within the crate to device-specific DOOCS servers such as the beam current server via ZeroMQ and stamped with a unique, shot-related number.

Along with management/central data switching and CPU units, an integral part of a MTCA crate is the timing-system receiver module. Synchronisation is based on a hardware timing protocol distributed through a dedicated optical fibre system. Event triggers, clock signals and bunch-related data are sent to all front-end electronic modules with accurate precision (10 ps RMS jitter). A variable bunch pattern for the individual undulator beam lines can be transmitted prior to a bunch train.

The timing system hardware is linked to the Machine Protection System (MPS). Based on well-defined error conditions the MPS can restrict or inhibit the number of bunches to be sent through a specific accelerator section (e.g. injector only). Approximately 130 MPS modules are distributed along the accelerator. Input signals are directed through a dedicated optical fibre system towards two master modules located near the injector and the dump kickers for final logical processing.

In addition to the standard control system interface a fast data-driven protocol is used to send bunch-related data to central DAQ nodes. The sustained overall data rate to the DAQ system is of the order of 1.3 GB/s. Several DAQ instances are connected to a 10 GbE backbone network and operated in parallel. The nodes synchronize the data received from the distributed DOOCS front-end servers and store the data which belong together as a common, uniquely stamped data structure in a shared memory. All data are stored on disk for a few weeks for further analysis and can optionally be saved on tape.

In order to improve application software development and to verify and tune the global system performance the so-called Virtual-XFEL test bed has been put in place. Simulated data are sent at full rate to a dedicated DAQ system which forwards the data to specific middle-layer processes running within the DAQ run time environment. These servers are dedicated to preparing data for visualization or running software loops such as the transverse or longitudinal feedback. Other servers will provide beam optics data and calculate the actual energy profile along the accelerating structures.

Operating the accelerator is based on graphical user applications. Most applications run in the so-called jddd environment which generically displays user panels based on panel-specific configuration data. In addition, rich client like applications coded in Java, MATLAB or Python will be provided by scientists for measurement purposes.

UNDULATOR CONTROLS

Three undulator systems are used to produce the photon beams. Each undulator system consists of an array of up to 35 undulator cells installed in a row along the electron beam. A single undulator cell itself consists of a 5 m long planar undulator segment and a 1.1 m long intersection housing a phase shifter, magnetic field correction coils, and a quadrupole mover. Four servo motors are used on each undulator to control the gap between girders with micrometer accuracy. The current of magnetic field correction coils as well as the gap of the phase shifter are adjustable as a function of the undulator gap [3].

System Architecture and Components

Each undulator system has a length of about 200 m and is controlled by a distributed control system. It consists of a central control node (CCN) and one local control node (LCN) per undulator cell communicating through a real-time capable (EtherCAT) network used for device and motion control and an ordinary network used for monitoring, remote access and maintenance. Both networks implement the so-called “redundant ring topology” tolerating one single point of failure. The undulator control system provides flexible and sophisticated control of the K-parameters of all involved undulators. It allows full control by the accelerator control system and control of a limited set of relevant undulator parameters (gap, taper) by the beam line users.

In operational mode the CCN receives motion commands from the accelerator control system and translates those into individual commands for each LCN. It collects status data from each LCN and sends it back to the accelerator control system. In addition, it performs various maintenance tasks (updating device configuration data and operating system software) and provides an interface to the users.

The LCN is a Programmable Logic Controller (PLC) running on an industrial PC. It controls all Beckhoff TwinCAT-compliant front-end devices belonging to each single undulator cell such as motors, beam trajectory correctors, and valve controllers. In addition, it is involved in the synchronized tuning of undulator cells to the desired K value.

A configuration database and an engineering data management system complete the undulator control system.

PHOTON BEAMLINE CONTROLS

The supervisory control and data acquisition system of the photon beam lines must integrate hundreds of distributed and very different components such as mirrors, large 2D detectors or sample-handling systems into one homogenous software framework. It interfaces to programmable logic controllers for equipment control, fast FPGA-based electronics for timing and data acquisition, CPU and GPU based algorithms for online data monitoring, distributed calibration and analysis tasks.

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Conceptual Design

To cope with diverse integration needs yet still keep a homogenous interface to users and developers, a novel software framework (Karabo) [4] has been created. The remote end-points (devices) of Karabo control beam line equipment (e.g. motors, pumps, and valves) or handle concurrent data processing and analysis tasks.

Devices communicate through a message-oriented middleware using a logically central but physically clustered asynchronous and event-driven broker mechanism for message routing. Additionally, specific point-to-point connections between devices can be established and are used for shipping large and fast data as needed for DAQ and processing pipelines.

Devices are completely self-descriptive regarding their parameters and functions. Hence, once loaded (plugin technology) a device is automatically controllable through a multi-purpose graphical user interface (GUI). Parameters and commands of any device can be composed into custom expert panels by dragging and dropping. Sequencing, scanning or other high level tasks are implemented in the form of Python macros, which - within the GUI - can be edited, executed and graphically controlled in expert panels.

Programmable Logic Controller Interfaces

Real-time synchronization and equipment protection relevant hardware is controlled via TwinCAT-compliant components and PLCs. Hundreds of physical devices such as motors or temperature sensors are being integrated by device-specific field bus terminals such as digital/analog inputs or outputs, motor drivers, encoder interfaces, and serial line drivers.

Groups of functionally related terminals mounted in crates are connected via a daisy-chained EtherCAT line to a common PLC. Using a specialized TCP/IP protocol each self-descriptive hardware or IO-channel is automatically reflected in the photon beam line control system as a Karabo device instance.

Fast Electronics and DAQ Interfaces

The architecture of the beam line data acquisition system foresees five layers: detector front end electronics, front end interfaces, PC farm layer, online data cache with computing clusters, and offline data archiving with offline computing clusters.

All detectors and sensors capable of acquiring data at the pulse frequency of 4.5 MHz are provided with synchronization signals, clocks and beam related metadata (such as unique bunch train IDs) from the common accelerator timing system. Sensor signals requiring digitization are treated using FPGA based modular digitizer systems and the MTCA.4 form factor. An in-house developed firmware framework facilitates algorithm implementation of the FPGA using graphical programming tools based on Simulink [5]. In addition, register mappings and variable descriptions are exported as Karabo-readable XML files allowing instantaneous control system integration.

The large volume of data streams produced by multiple detectors (e.g. up to 10 GB/s of image data by a single 2D MPixel detector) and sensors are handled in the PC farm layer. Efficient handling of this huge data volume requires large network bandwidth (10 GbE switched links) and properly structured and tuned computing capabilities (PC layer, storage systems, and analysis clusters) interconnected by an Infiniband fabric. The PC layer nodes are highly optimized Karabo devices which periodically receive bursts of image datagrams, which need to be correlated with other fast and slow data. Data are integrated based on bunch train ID and forwarded to the storage system and to the online computing farm for further analysis. All PC layer devices are synchronized and orchestrated via the same finite state machine using a single-instance Run Controller device.

CRYOGENIC AND UTILITY CONTROLS

Control systems for cryogenic equipment are similar to process control systems for refineries or chemical plants. This is the domain of PLCs as deterministic calculations and control loops are here mandatory. PLCs are also partly used for the cryogenic system but only in those cases where machine protection or special turnkey system requirements apply. In general all process control functionalities reside in EPICS IOCs. The majority of the control functions (about 80%) consists of control loops and digital logic. The remaining 20% is implemented in complex state notation language programs used for sequential operations, state based operations as well as supervisory controls.In contrast, utility controls rely nearly 100% on PLC controls for their turnkey systems.

All parts of the cryogenic infrastructure are controlled by the same control system based on EPICS. Cryogenic and utility controls share the same control infrastructure. While the EPICS IOCs basically run basically core software with some custom extensions, the operators work at consoles running Control System Studio (CSS), which provides plugins for synoptic displays, trending, alarming, etc.

Continuous Operation and Reliability

Cryogenic systems typically run in a 24/7 mode with run periods of one year and more. This defines basic requirements for the control equipment. Sensors and actors as well as the process controllers must fulfill these requirements. Redundant sensors are in place wherever they are buried inside cryogenic boxes. Redundant process controllers are in place for every critical component. In addition redundant power supplies and networks are used to be prepared for component failures. This philosophy is in place throughout the whole control system.

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The I/O System

Cryogenic systems are widely distributed. Even signals forming logical units may be spread over several hundred meters. I/O components are thus integrated into the system by means of Profibus field buses [6]. Profibus comes in two flavors: Profibus DP und Profibus PA where the latter also provides the power over the wires to the equipment. Individual Profibus nodes may consist of intelligent controllers gathering several tens of different signals as well as intelligent sensors and actors which in turn are connected to the PA variant of Profibus. The number of Profibus nodes adds up to 540 and results in 12.700 EPICS records.

Diagnostic Tools and Archiving

Widely distributed systems require good diagnostic tools with remote access to all basic information to diagnose error states and failures. In this case all Profibus lines are connected to individual diagnostic gateways which provide diagnostic information based on html (web) pages. In addition to this online information many diagnostic data are collected in the archive system for post mortem analysis.

INTEROPERABILITY

Basically all control systems used to operate the European XFEL are able to exchange a limited set of information between each other through a common Ethernet network. However, remaining issues related to naming conventions or authorization concepts might still require attention. In addition timing relevant data such as events or unique bunch train IDs can be distributed by the common accelerator timing system.

In order to facilitate device control and beam operation, both systems (DOOCS, TINE) used for accelerator control are tightly interconnected at both the client and server level. On the one hand the DOOCS client API can access any TINE server. On the other hand DOOCS servers can be configured to become defacto TINE servers. However, native TINE servers do not include DOOCS-specific DAQ system software, limiting the application of such servers to specific use cases.

The undulator control system integrates seamlessly into DOOCS. Each undulator system provides its own DOOCS-like server. Both experiment users and accelerator operators use DOOCS clients to control the undulators.

To facilitate the inter-communication with accelerator controls both Karabo and DOOCS clients will embed the others client API. In addition, Karabo must also integrate various in-kind contributions from external control systems (such as high-energy lasers, split and delay lines, etc.).

The interoperability between the cryogenic and the accelerator control system is still being discussed. Established solutions exist to exchange data between EPICS and DOOCS as well as TINE.

PROJECT STATUS

The installation of the general and in particular the novel MTCA infrastructure is progressing. Most aspects of the front-end hardware and software are in successful, routine operation at FLASH. Application development for the accelerator controls is still on-going. New software is either being tested or put into service at FLASH and the Virtual-XFEL simulation environment or directly in the gradual commissioning of already completed accelerator sections. So far the required performances have been demonstrated.

The basic concept of the undulator control system has been successfully tested at a mock-up. Extending the concept to a real undulator system and implementing the final controls software is under way.

Karabo is close to being fully featured. As of this writing it already controls a large pump-probe laser setup, several test stands (involving task like vacuum, motion, detector calibration and alignment, etc.) and will be in production for controlling the photon beamline components currently being installed in the SASE1 tunnels.

The cryogenic plant is successfully in operation for the past half year. Along with the installation of the accelerating structures the cryogenic equipment of the distribution system will be installed and tested. According to the staged technical commissioning of the accelerator sections, the cryogenic and utility control system will be put into service.

REFERENCES

[1] H. Schlarb et al., „The Case of MTCA.4: Managing the Introduction of a New Crate Standard at Large Scale Facilites and Beyond“, ICALEPCS’13, San Francisco, USA, October 2013, FMOPPC081, p. 285 (2013); http://www.JACoW.org

[2] P. Duval et al., Control System Interoperability, an Extreme Case: Merging DOOCS and TINE”, PCaPAC’12, Kolkata, India, December 2012, THIB04, p. 115; http://www.JACoW.org

[3] S. Karabekyan et al., “The Undulator Control System for the European XFEL”, IPAC’12, New Orleans, USA, May 2012, THPPR002, p 3966 (2012); http://www.JACoW.org

[4] B.C. Heisen et al., Karabo: An Integrated Software Framework Combining Control, Data Management, and Scientific Computing Tasks“, ICALEPCS’13, San Francisco, USA, October 2013, FRCOAAB02, p. 1465 (2013); http://www.JACoW.org

[5] B. Fernandes et al., High Level FPGA Programming Framework Based on Simulink”, ICALEPCS’13, San Francisco, USA, October 2013, TUPPC086, p. 776 (2013); http://www.JACoW.org

[6] M. Clausen et al.,"PROFIBUS in Process Controls", PCaPAC’14, Karlsruhe, Germany, October 2014, WCO2013, p. 16; http://www.JACoW.org

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