ADAPTABLE CONTROL SYSTEM FOR THE PHOTON BEAMLINES AT THE EUROPEAN XFEL: INTEGRATING NEW DEVICES AND TECHNOLOGIES FOR ADVANCED RESEARCH

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Abstract

The European XFEL is an X-ray free-electron laser (FEL) facility located in Schenefeld, in the vicinity of Hamburg, Germany. With a total length of 3.4 kilometers, the facility provides seven scientific instruments with extremely intense X-ray flashes ranging from the soft to the hard X-ray regime. The dimension of the beam transport and the technologies used to make this X-ray FEL unique have led to the design and buildup of a challenging and adaptable control system based on a Programmable Logic Controller (PLC). Six successful years of user operation, which started in September 2017, have required constant development of the beam transport in order to provide new features and improvements for the scientific community to perform their research activities.

The framework of this contribution is focused on the photon beamline, which starts at the undulator section and guides the X-ray beam to the scientific instruments. In this scope, the control system topology and this adaptability to integrate new devices through the PLC Management System (PLCMS) are described. In 2022, a new distribution mirror was installed in the SASE3 beam transport system to provide photon beams to the seventh and newest scientific instrument, named Soft X-ray Port (SXP). To make the scope of this paper more practical, this new installation is used as an example. The integration in the actual control system of the vacuum devices, optic elements, and interlock definition are described.

INTRODUCTION

With a total length of 3.4 kilometres, the European free-electron laser (FEL) facility [1], sets itself apart through its scale and technical capabilities. Currently, seven scientific instruments are provided with extremely intense X-ray flashes ranging from the soft to the hard X-ray regime by accelerating electrons up to 17.5 GeV in a superconducting (SC) linear accelerator [2]. The facility's singularity is further underlined by its collaborative aspect, involving twelve shareholder countries in the project's success. It also distinguishes itself in research with a wide range of scientific disciplines, including physics, chemistry, biology, materials science, and earth science. Finally, the facility's uniqueness is underlined by the scale, the multitude of elements, and the architecture of its control system. Based on a Programmable Logic Controller (PLC), it has well over a hundred PLCs with an important variety of devices to control. Moreover, to offer an intuitive user interface, the PLCs are interfaced with an in-house Supervisory Control and Data Acquisition (SCADA) system named Karabo [3].

From the start of user operation in September 2017 to the present year, when the commissioning of a Soft X-Ray Port (SXP) [4] instrument started, a substantial series of upgrades and enhancements have been implemented. In line with the new research requirements, the adaptability of the control system is required to keep this facility up to date, integrating new devices with cutting-edge technologies.

This paper describes the different elements constituting this adaptable control system and an illustration of device integration.

First, the PLC Management System (PLCMS), a software tool to automatically generate PLC projects, and Karabo are addressed. Then, the control system topology of the photon beamline and the device used as an example, a mirror chamber, are described. The workflow to integrate this new device into the control system is also illustrated. Finally, challenges and considerations for the future perspectives are outlined.

The scope of the paper is limited to the photon beamline, which starts at the undulator section and guides the X-ray beam to the scientific instruments. The control system concept is the same for the scientific instruments, but the topology can differ from the photon beamline control system.

THE PLCMS

In the context of expanding hardware devices that need to be controlled and the significant use of PLCs at the European XFEL, a tool has been developed to automate the generation of PLC firmware projects [5]. This tool allows a quick generation of the PLC project to accommodate hardware modification. Developing standard components through a PLC framework has been the first main point to allow automatic generation. The framework is developed with Beckhoff TwinCAT [6] and contains different classes, known as Program Organization Units (POUs) in the IEC 61131 standard, and incorporates a wide range of standardised devices within the framework. Each of these standardized devices in the PLC framework is named soft device (SD), and each piece of hardware is linked to a corresponding instance of the SD.

The Electronic and Electrical Engineering (EEE) group at European XFEL has developed the PLC management system (PLCMS) to automate the generation of PLC projects. The PLCMS is developed using the Python 3 programming

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language. The PLCMS generation process is illustrated in Fig. 1.

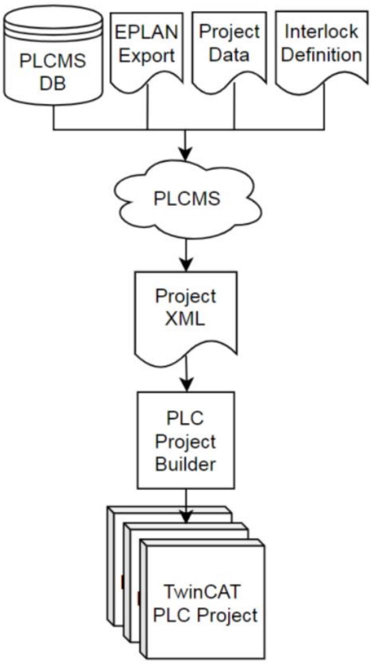


Figure 1: Architecture of the PLCMS generation process.

Four inputs are provided to the PLCMS script for automatically generating the PLC projects. TwinCAT is featured with an eXtended Automation Engineering interface (XAE), assisting the automated generation of TwinCAT PLC projects using additional scripting languages. An interface has been established with XAE, the PLC Project Builder, to generate the TwinCAT project based on all the data from the PLCMS script, formatted in XML.

The PLCMS controls and checks all input data's consistency. It confirms that the SD is supported, cross-checks the data type of each SD instance, and ensures compatibility with the framework.

KARABO

Karabo is an in-house Supervisory Control and Data Acquisition (SCADA) system, similar to EPICS [7] or TANGO [8] systems. Requirements coming from specialized detectors and instruments, and the outstanding pulse structure of the photon beam (reaching up to 27000 photons pulses per second, with 10 Hz train pulses into the MHz regime [9]), result in elevated data rates and the requirement of data calibration before analysis.

Karabo provides a Graphical User Interface (GUI) and data analysis tools to the scientific community, operators, and technical experts. It uses device-based communication via a central message broker. A command-line interface enables the creation of reusable combined commands structured in macros. Karabo controls equipment ranging from motors, pumps, valves, and simple switches, to effectively managing high data rate devices, such as X-ray detectors.

In most cases, the controlled hardware is interfaced with the Beckhoff PLC. Specific equipment can also be directly integrated into Karabo via TCP/IP connections, like cameras or multi-axis motion systems.

Karabo also plays a crucial role in data analysis during and after the experiment. Data from detectors move through the data acquisition system (DAQ). Raw data is archived following a rigorous data policy [10]. Since June 2023, Karabo has been released to the public domain as free and open-source software [11]. It is now available under a mixed MPL 2.0 and GPLv3 licensing scheme [12].

PHOTON BEAMLINE TRANSPORT CONTROL SYSTEM

At European XFEL, the photon beamline, which guides the photon beam from the undulator area to the scientific instruments, is an arrangement of vacuum elements, X-ray optical devices, and diagnostics systems. The photon beam transport is around 1 km long and is located in underground tunnels. Figure 2 shows a detailed example of SASE1 beam transport. This figure illustrates the large variety of devices present in the beam transport that guide the photon beam.

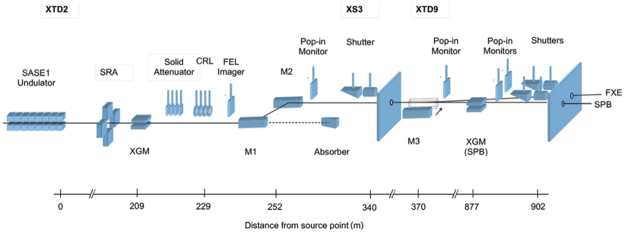


Figure 2: Schematic SASE1 beam transport.

A ring topology was chosen as the network architecture to control the beam transport devices. We refer to this setup as a "loop". A loop is based on one PLC with an array of local control crates. Conceptually, each local control crate can be viewed as local adaptable electronics to interface different devices. The local crate is an in-house design based on Beckhoff Automation technologies. The EtherCAT communication protocol is deployed between the master PLC and local control crates through a redundancy module, enabling bidirectional communication between the PLCs and the local crates across the network. This design mitigates the risks associated with a single point of failure and enhances the system's robustness and reliability. Typically, a minimum of three loops are deployed in each SASE and serve different purposes:

- **VAC loop:** Interface to vacuum devices like valves, pumps, or gauges [13].
- **MOV loop:** Mainly existing for the X-ray optical devices that require motion control. Accessing components such as stepper motors, piezo actuators, encoders, or positioners.
- **EPS loop:** EPS, an acronym for Equipment Protection System, interfaces all safety equipment-related devices. This loop incorporates a wide range of sensors involved in the integrity of the equipment, including water sensors, temperature sensors, or position switches.

The EPS loop also has an essential role concerning machine safety, as it monitors and interlocks the beam, based on various conditions. This loop has the capability to limit or stop the beam through a direct connection to the Machine Protection System (MPS) managed by DESY [14].

In specific scenarios, introducing additional loops has been advantageous in limiting the data flow rate handled by the PLCs and in increasing the clarity. Figure 3 illustrates the architecture of the VAC loop for the beam transport. The local control crates are fixed inside the electrical rack along with the different controllers.

Two connection types are established for the equipment:

- **Wired connection:** Components are directly linked to the local control crate.
- **Interfaced connection:** Devices need an intermediate controller for operation.

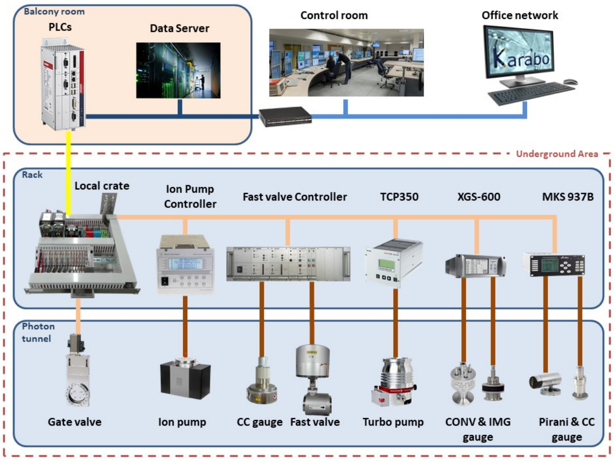


Figure 3: Overview of the VAC loop topology and the types of connection.

The local crates, utilizing PLC control system technology, are not the only available interface connection for the equipment in the beam transport system. Fast data acquisition or device-triggering is also essential. Building upon the DESY control system infrastructure [15], a MicroTCA system following the MTCA.4 standard has been integrated across several racks in the tunnels.

This MicroTCA system brings three additional functionalities:

- **Timing system:** Synchronisation and timing coordination with the beam is achieved through this system.
- **Machine protection system:** This system monitors the equipment and the overall operation, detecting and responding to potential anomalies.
- **Data acquisition system:** High-speed and efficient data collection for fast processing.

MIRROR CHAMBERS

X-ray mirrors guide the beam to the scientific instruments [16]. The mirrors are installed in a vacuum chamber, named Chambers for HOrizontal Mirrors (CHOM). A representation of this CHOM device is provided in Fig. 4.

Five degrees of freedom can be operated using out-of-vacuum stepper motors. two-phase stepper motors with 200 steps per 360° perform the motion. To ensure high accuracy and requisite torque, a gearbox is used with each stepper motor. Absolute encoders with a Synchronous Serial Interface (SSI) provide an accurate position signal of the mirror with a resolution of 12 bits. Fine adjustments can be made using in-vacuum piezo actuators on the pitch and roll motions.

The vacuum in the CHOM is maintained at the pressure range of 10^{-9} mbar through an ion pump of 300 l/s. Pirani and cold cathode gauges serve as complementary pressure measurements in the chamber. The CHOM design incorporates viewport flanges, with a fixed camera and controlled light, enabling remote visual inspection.

The bendable mirror has a trio of capacitive sensors positioned on the mirror's backside to enable the calculation of the bending radius. These sensors deliver micrometre range data.

Finally, the distribution mirror has magnetic switches to the Tx and Ry axes. These magnetic elements serve as safety switches, contributing to the safety interlock system and providing information about which scientific instrument is receiving the photon beam.

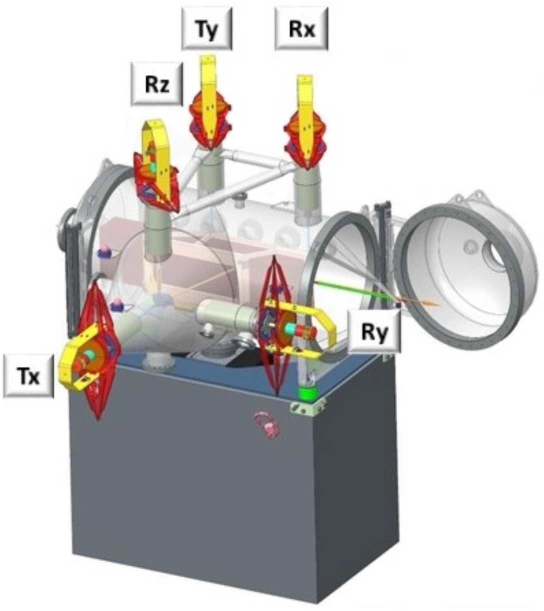


Figure 4: 3D representation of the mirror chamber (CHOM).

SASE3 CHOM INTEGRATION

During the summer maintenance period in 2022, a new CHOM was installed in the SASE3 tunnel that needed to be integrated into the control system. This new distribution mirror, named M6, can direct the X-ray beam to the scientific instrument SXP.

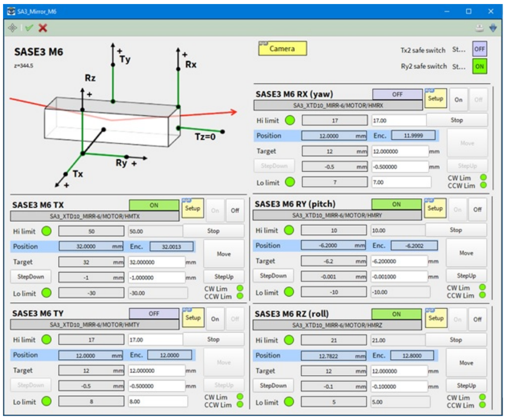
To adapt the current control system to this new device, the initial step involves the creation of an electrical diagram. Complementary data are integrated during this design phase to provide relevant information for the PLCMS, such as SD name or EtherCAT addressing, outputting an XML file.

In parallel, technical experts in different domains write the interlock conditions specific to the new device. Two distinct PLC loops are affected by these new interlock conditions: the VAC loop for the triggering of the sector valves and the EPS loop for the beam authorisation.

The export file from the electrical diagram software (EPLAN), encompassing design and configuration details, along with the interlock definitions, is provided to the PLC engineers for generating the TwinCAT project. Data of particular configurations and initialization to accommodate different hardware has been read and stored within another file. These inputs channelled to PLCMS, generate an XML file, which is the base for the PLC project builder to generate the updated TwinCAT project, incorporating the new M6 CHOM.

Including new devices in the control system also entails hardware modification. A new local crate, which belongs to the MOV loop, has been built according to the hardware specification of the CHOM. The five stepper motors and absolute encoder are driven by the respective Beckhoff terminals ES7041 and EL5042. Fine positioning of the mirror with the piezo actuator is controlled with analogue input and output.

Considering a new vacuum sector becomes operational, modifying the existing local crate dedicated to controlling the vacuum equipment is necessary. Two additional gate valves are “wire connected” at the local crate to create the new vacuum sector. New controllers for the CHOM ion pump and gauges are installed in the rack and interfaced to the local crate of the VAC loop.



SASE3 M6 RX (yaw) OFF Setup On Off
SA3_XTD10_MIRR-6/MOTOR/HMRX
Hi limit 17 17.00 Stop
Position 12.0000 mm Enc. 11.9999
Target 12 mm 12.000000 mm Move
StepDown -0.5 mm -0.500000 mm StepUp
Lo limit 7 7.00 CW Lim CCW Lim

SASE3 M6 TX ON Setup On Off
SA3_XTD10_MIRR-6/MOTOR/HMTX
Hi limit 50 50.00 Stop
Position 32.0000 mm Enc. 32.0013
Target 32 mm 32.000000 mm Move
StepDown -1 mm -1.000000 mm StepUp
Lo limit -30 -30.00 CW Lim CCW Lim

SASE3 M6 RY (pitch) ON Setup On Off
SA3_XTD10_MIRR-6/MOTOR/HMRY
Hi limit 10 10.00 Stop
Position -6.2000 mm Enc. -6.2002
Target -6.2 mm -6.200000 mm Move
StepDown -0.001 mm -0.001000 mm StepUp
Lo limit -10 -10.00 CW Lim CCW Lim

SASE3 M6 TY OFF Setup On Off
SA3_XTD10_MIRR-6/MOTOR/HMTY
Hi limit 17 17.00 Stop
Position 12.0000 mm Enc. 12.0000
Target 12 mm 12.000000 mm Move
StepDown -0.5 mm -0.500000 mm StepUp
Lo limit 8 8.00 CW Lim CCW Lim

SASE3 M6 RZ (roll) ON Setup On Off
SA3_XTD10_MIRR-6/MOTOR/HMRZ
Hi limit 21 21.00 Stop
Position 12.7822 mm Enc. 12.8000
Target 12 mm 12.000000 mm Move
StepDown -0.1 mm -0.100000 mm StepUp
Lo limit 5 5.00 CW Lim CCW Lim

Figure 5: KARABO GUI panel for M6 mirror.

Due to the architecture of Karabo, the updated PLCs interact with Karabo via TCP/IP connections. Through this dynamic interaction, the updated PLCs inform Karabo of the newly established SD instances. The new equipment becomes available in the control system after the PLC updates and the reconnection with Karabo.

X-ray optics, vacuum, and safety experts now have at their disposal tools and devices available through the graphical user interface (GUI) of Karabo (Fig. 5). This facilitates the creation of Karabo scenes and automated macros to control the newly integrated CHOM device.

CONCLUSION, FUTURE PERSPECTIVES, AND CONSIDERATION

Adaptability of the control system is essential for a facility such as the European XFEL. Smoothly integrating new technologies without overhauling the existing control system is necessary. Significant efforts have been realized, from conceptual design to practical application, developing tools and workflows that effectively meet these requirements. Key achievements include the PLCMS for TwinCAT project generation and the adaptation of EPLAN to facilitate structured export file generation. The utilization of standard electrical hardware for electronics interfacing or the establishment of a comprehensive naming convention for SD instances are also relevant accomplishments.

These examples underline the importance of standardisation, which is crucial for large control systems.

Following this guideline, multiple opportunities for enhancement remain. Currently, the utilization of distinct local crates for scientific instruments and beam transport opens possibilities for improvement. Based on the lessons learned from operational experience, ongoing developments try to bridge and consolidate hardware solutions between these two crates.

In terms of asset management, the European XFEL control system’s capabilities remain an area with potential improvement. Many equipment-related data are available, with the potential to implement an efficient asset management system including reporting, supervision, and alarms. Progress can be achieved within the current control system to specify, organize and implement a robust asset management system, thereby increasing overall hardware reliability.

SUMMARY

European XFEL has established an adaptable control system through a range of innovative tools and concepts, including the PCLMS and the PLC framework. The standardization of software, hardware, and procedures enables the management of an expanding and dynamic control system for the photon beam transport. The current control system demonstrates its capacity to integrate new devices and cutting-edge technologies to meet the demand for advanced research.

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