EUROPEAN XFEL PHASE SHIFTER: PC-BASED CONTROL SYSTEM

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Abstract

The Accelerator Technology Unit at CIEMAT is in charge of part of the Spanish contribution to the European X-Ray Free-Electron Laser (EXFEL) [1]. This paper presents the control system of the Phase Shifter (PS), a beam phase corrector magnet that will be installed in the intersections of the SASE undulator system. Beckhoff has been chosen by EXFEL as its main supplier for the industrial control systems. Beckhoff Twincat PLC architecture is a PC-based control technology built over EtherCAT, a real-time Ethernet fieldbus. The PS is operated with a stepper motor, its position is monitored by an incremental encoder, and it is controlled by a Twincat-PLC program using the TcMC2 library, an implementation of the PLCopen Motion Control specification. A GUI has been developed in LabVIEW instead of using Beckhoff visualization tool. The control system for the first and second prototype devices has been developed in-house using COTS hardware and software. The specifications request a repeatability of ($\pm 50 \mu$m) in bidirectional movements and ($\pm 10 \mu$m) in unidirectional movements. The second prototype can reach speeds up to 15 mm/s.

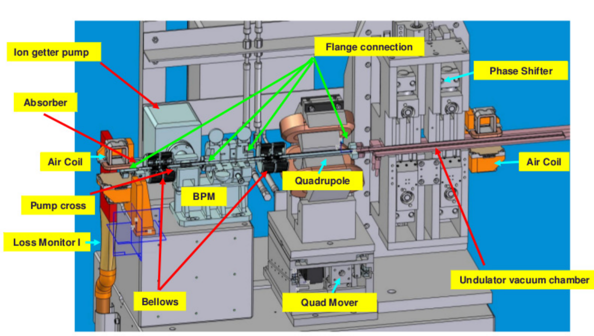

Figure 1: EXFEL Undulator System intersection.

INTRODUCTION

The undulator systems of the European XFEL have a total approximate length of 200 m. They are divided into cells which comprise a 5m long undulator segment and a 1.1 m long intersection, Fig. 1, where several devices needed to adjust the beam properties are located [2]. 92 sets of components for the intersections will be supplied by CIEMAT, as part of the spanish in-kind contribution to the European XFEL. The control system is also a part of this contribution.

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One of the components of the intersection is the Quadrupole Mover (MV) [3], a biaxial (X-Z) moving table that aligns a 70 kg quadrupole magnet within ± 1.5mm in two dimensions with repeatability better than $\pm 1 \mu$m. Two 5-phase stepper motors move the table in the horizontal and vertical directions. Positions are monitored with two LVDTs.

Another device is the Phase Shifter [4], see Fig. 2. Its function is to correct the phase of the electron beam with respect to that of the radiation field when the wavelength is changed. This is achieved by opening or closing the gap between two sets of magnetic modules geared by a double left-right hand threaded lead screw, which, in turn, is actuated by a stepper motor fitted with a 40:1 gearbox [5].

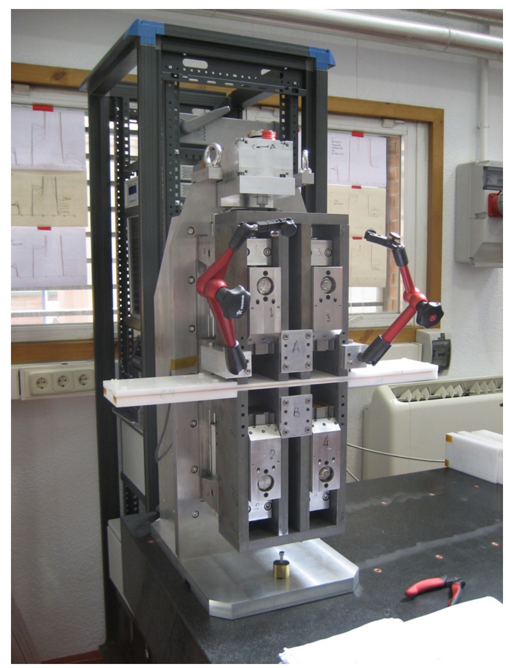

Figure 2: Phase Shifter.

The Intersection Control Rack (ICR) will house an EtherCAT bus coupler plus all the modules needed for operation of the PS and the Quadrupole Mover. Electrical protection modules and low-noise power supplies are to be mounted in order to improve its long term reliability. The bus coupler links the ICR to the Undulator Rack, where an embedded PC will control the corresponding undulator cell.

For protoype testing (MV, PS), dedicated control cabinets have been assembled with the required Beckhoff control modules (bus coupler and I/Os), along with motor drivers, power supplies and signal conditioning units. The

PLC control unit, for development purposes, is always a standard PC running Beckhoff Twincat PLC under Windows, with an extra Ethernet PCI card connected with a standard cat-5 cable to the EtherCAT bus coupler in the cabinet. To expand the possibilities of the native Beckhoff SCADA interface, a GUI has been written in LabView to operate the PS from the PC. This is part of CIEMAT's effort to produce a software which can be used for both testing and validation of the prototypes and the production batch.

In this paper, the components of the PS control system are presented in detail.

PHASE SHIFTER CONTROL SYSTEM

PC-based Automation

Many flavours of PC-based automation solutions are being offered nowadays by all major control technology companies. Due to increasing performance and decreasing cost of hardware components, embedded PCs equipped with flash memory cards or solid-state drives can be used in an industrial environment replacing the traditional PLCs.

Following hardware progression, many software packages populate the market, turning any PC into a real-time controller, and thus allowing programming, diagnostics and configuration of devices connected either to the PC directly or through fieldbus cards, while ensuring deterministic real-time behavior. There is also a growing presence in the automation industry of real-time communication protocols based on Ethernet which are gaining market share to traditional field buses due to the already important existing base of ethernet cabling. We have used one of these protocols, EtherCAT, released by Beckhoff in 2003 [6], which is, according to manufacturers, able to exchange many distributed signals with cycle times below 100 μs [7].

Control Hardware

The hardware modules have been selected according to the demands imposed by the design specifications When the gap aperture is under 20 mm, the magnetic forces are very strong. Therefore special care has been taken in the selection of the motor drive to supply the needed torque when operating in microstepping operation at the target speed.

Summarising, the main hardware components of the PS and its control system include:

- A 5-phase Oriental Motor stepper motor (RK 564 AMCE) and its driver (RKD514LM-C).
- A Renishaw optical encoder (RGH22D) with 1 μm resolution and homing mark.
- Beckhoff PLC modules, (see Fig. 3) , listed in Table 1.
- 2 Limit switches, Saia T85 5E4

The first PS prototype used a 2-phase stepper motor and was controlled directly with a Beckhoff module without motor driver. Such philosophy was later abandoned due to excessive mechanical noise and motor vibration. After extensive testing, the EL7041 stepping motor controller

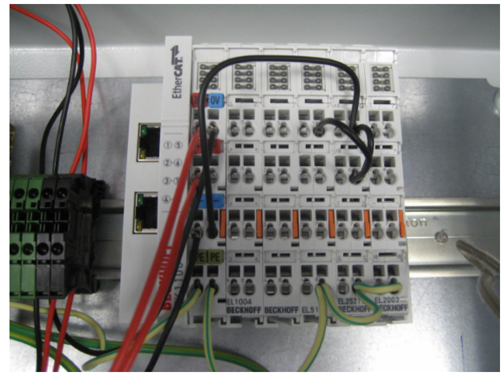

Figure 3: PS control modules before wiring.

Table 1: Beckhoff Modules Used

Module	Description
EK1100	EtherCAT coupler
EL1004	Digital inputs for limit switches
EL5101	Incremental encoder module
EL2521	Pulse train output for motor control
EL2002	Digital outputs for motor brake
EL3204	Terminal for temperature readings (PT100)

module was found to be responsible for this behaviour. A new release of this module, with an upgraded firmware and hardware, was tested afterwards with the same motor and the results were much better but still inferior to the option of equipping the PS with a motor and driver from the same manufacturer and using a Beckhoff pulse train digital output module to control the driver, a solution which gives a better performance and, subsequently, was adopted for the second PS prototype.

Software

The PS prototypes are controlled by a PC running Beckhoff Twincat PLC, that acts like a virtual machine running the PLC program. This program, developed at CIEMAT, has been coded in Structured Text following the IEC 61131-3 standard. Twincat PLC can run up to four PLC runtimes in a PC, and, specifically for motion control, Twincat PLC NC offers the TcMC2 library which is compliant with the PLCopen Motion Control standard [8]. CNC axes are referenced by the derived datatype AXIS_REF. Several function blocks (FB) are available for single or multiple axis control and reading their status variables.

As other projects were being developed at CIEMAT for EXFEL using stepper motors, it was decided to create a Twincat PLC library, MotorCommon.lib, to implement all these subsystems. This library uses a mix of basic function blocks available in the TcMC2 library and in-house developed functions better suited to the project needs. Any drive configured as an axis in Twincat PLC NC can be defined as an instance of the *MotorControlWTimedBrakeAutoPow* function block. A wrapper (i.e. MoverMotor or Phase-ShifterMotor) adapts the FB to any motor characteristics. For example, the PS stepper motor comes equipped with an electromagnetic brake and the motor windings can be activated or deactivated following an on/off signal. Due to the incremental nature of the position feedback, the PS wrapper defines also a homing procedure that has to be carried out when the device is started up or after an error. Every motor operational parameter, such as brake delay time, deadband position, backslash compensation, timeout and maximum operating temperature can also be configured.

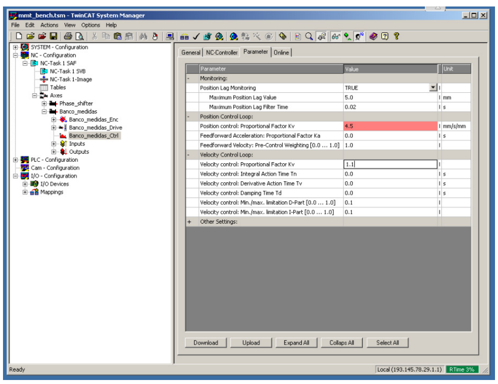

Figure 4: Axis configuration in Twincat System Manager.

The Twincat System Manager (see Fig. 4) is the configuration tool for the EtherCAT system, the PLC program, the I/O modules and the mechanical axes. A motor, or more generically a drive, can be defined as a Computer Numerical Control (CNC) axis and then linked to the corresponding modules. An axis has two basic elements, plus a third one: i) the actuator or drive, ii) the encoder or feedback, and iii) the controller or control policy. For instance, the PS axis is linked to both a pulse train output card (EL2521) and an incremental encoder card (EL5101). The controller can also be chosen and configured. The PS uses a position P control plus velocity PID with torque. The parameters for this controller have been manually tuned.

Although Twincat PLC comes with its own visualization tool, a classical SCADA GUI package, LabVIEW GUIs (see Fig. 5) have been developed in-house to take advantage of LabVIEW flexibility. The communication between LabVIEW and Twincat PLC has been achieved by using the Beckhoff TcADSdll.Dll library, which organises data exchange between Windows programs and Twincat. On top of that, a series of functions have been created to control the PLC from our GUI: start or stop the PLC, read variables and send data and commands. However this communication is asynchronous to the PLC cycle, forcing the Labview programm to constantly interrogate the TwinCAT server for changes in the status of signals. This could be a drawback for operation but does not pose any problem for testing and measurement. The validation of the series production will also be done automatically by a LabVIEW

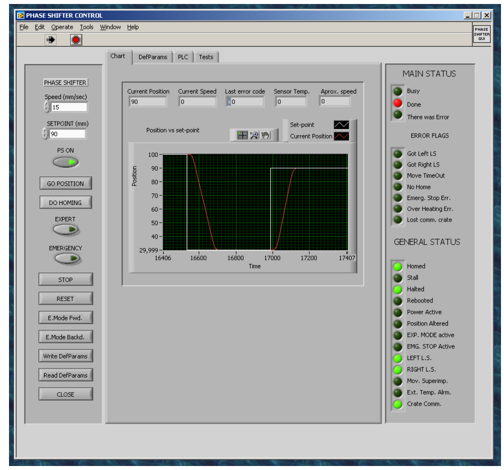

Figure 5: PS control LabVIEW GUI.

program, its development is under way.

RESULTS

The magnetic and mechanical measurements of the two prototypes have been reported in [9]. The first prototype achieved a repeatability of ($\pm 57 \mu$m) in bidirectional movements, slightly over the limit, due to some mechanical problems that were corrected in the second prototype.

Some requirements have evolved over time, such as the gap opening speed. The latest request is that the PS shall follow the undulator, at speeds over 10 mm/s. Speeds up to 15 mm/s have been achieved with the second prototype. Preliminary measurements of this prototype, (see Fig. 6) show that positioning errors are within limits.

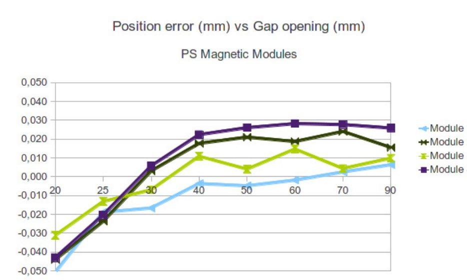

Figure 6: 2nd PS prototype preliminary measurements.

MAGNETIC MEASUREMENTS TEST BENCH

The Magnetic Measurements Test Bench (MMTB) (see Fig. 7) has been developed at CIEMAT as a tool to calibrate and measure the magnetic field of the Phase Shifter, in order to validate the magnetic design of the PS [10]. A linear actuator controlled by a dedicated Beckhoff module moves a coil inside the PS gap. This coil is connected to a fluxmeter which integrates the magnetic flux, that is then read by a 24-bit ADC module to construct the $\overrightarrow{B}$ field integral after post-processing. The PLC controls both axes (PS and MMTB) and records position, speed and magnetic field values for further analysis. The position is monitored by an incremental rotational encoder. Its control software been written using the same libraries (PLC and LabVIEW) than the PS. Special care has been taken to synchronize the values that are written to a file by the PLC. Initially, after data analysis, a delay of a few milliseconds was found, dependent of the speed, so that in the Field Integral versus Position graph, the "in" cycle (when the coil is moved inside the PS) and the "out" cycle did not match. This is probably caused by the way the PLC works, as it reads the variables first and produces the timestamp at the moment of writing to the file.

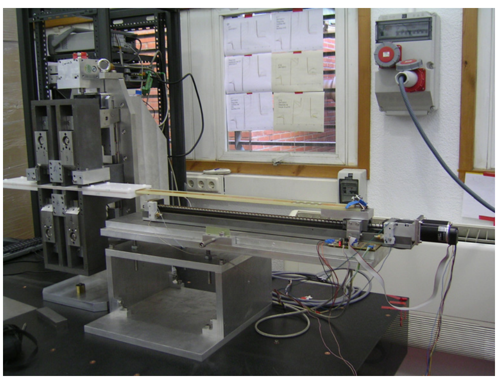

Figure 7: Phase Shifter and MMTB.

CONCLUSIONS

The Accelerator Technology Unit at CIEMAT is in charge of the design, manufacturing and delivery of several components to be installed in the 92 intersections of the Undulators System of the European XFEL, in particular, the Phase Shifter, the Quadrupole Mover and the Intersection Control Rack. All the control hardware has been implemented using commercial devices. In addition we have written a Beckhoff Twincat PLC library to encapsulate all devices as CNC axes within the Beckhoff architecture. GUIs have been created, based on an in-house developed LabVIEW library, able to communicate with the PLC runtime. As soon as the different prototypes have been available for testing in our labs, the integration of the control system has been quickly achieved. A fully automatic measurement procedure have been implemented. The first prototype achieved a repeatability of ($\pm 57\mu$m), over the limit. The second prototype is now being tuned and the preliminary measurements have been satisfactory.

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