

USE OF AUTOMATION IN COMMISSIONING PROCESS OF THE UNDULATORS OF THE EUROPEAN X-RAY FREE ELECTRON LASER

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Abstract

For operation of the three undulator systems of the European XFEL, a total of 91 undulators are needed and have been produced. For production, magnetic measurements, tuning and commissioning of these devices only two years were foreseen by the project schedule. For these purposes, automated and optimized procedures were needed to accomplish a number of workflows, time-consuming adjustments and commissioning tasks. We created several automation programs which allowed us to reduce the time spent on the commissioning of the control system by an order of magnitude.

OBJECTIVES

All undulators are planned to be commissioned and put into operation in two years, starting from 2013 until the beginning of 2015. Given the fact that European XFEL has three magnetic measurement labs available, 3 weeks were foreseen for commissioning of the control system and the magnetic measurements and tuning of each undulator.

For each undulator, the commissioning procedure includes the following main steps:

1. Installation and adjustment of the linear encoders to achieve an accuracy of $\pm 1 \mu\text{m}$.
2. Adjustment of the tilt angles of the undulator girders to better than $\pm 150 \mu\text{rad}$.
3. Alignment of the undulator relative to the magnetic measurement bench.
4. Magnetic measurements and field fine tuning.
5. Final measurements and documentation of magnetic properties of undulator.
6. Evaluation and implementation of the correction coefficients for rotary encoders of undulator-motors.
7. Calibration of the temperature sensors.

Items 3 to 5 are part of semi-automatized magnetic measurements and tuning procedures applied to each undulator. To proceed with these tasks, approximately 2.5 weeks are necessary. The items 1, 2, 6, 7, which took without automation 2 - 2.5 weeks, must be automated to be accomplished in less than 3 days.

BASIC APPROACH

The undulator control system is based on industrial components produced by Beckhoff Automation GmbH. Using the TwinCAT software, a programmable logic controller (PLC) can be run either on an industrial PC

which is used to control an undulator, or it can be run on a separate Windows PC carrying out the following steps:

- Initialization: Connection to the undulator PLC or to external controllers or devices, loading and initializing of configuration data.
- Data acquisition, depending on the configuration data.
- Data processing and analysis, graphical representation of the analysis results and calculation of required values.
- Formatting the output as required, such as creating ASCII tables, PDF protocols or configuration files for the undulator PLC

ADJUSTMENT OF THE LINEAR ENCODERS

The undulator gap is controlled by four servo motors. Each of them has its own, absolute rotary encoder. This allows an indirect measurement of the gap. A second, more precise system, is directly measuring the gap by means of two absolute linear encoders HEIDENHAIN LC 183 installed on both ends of the undulator girders (see Fig. 1). Both systems can be used alternatively to provide feedback to the motion control system.

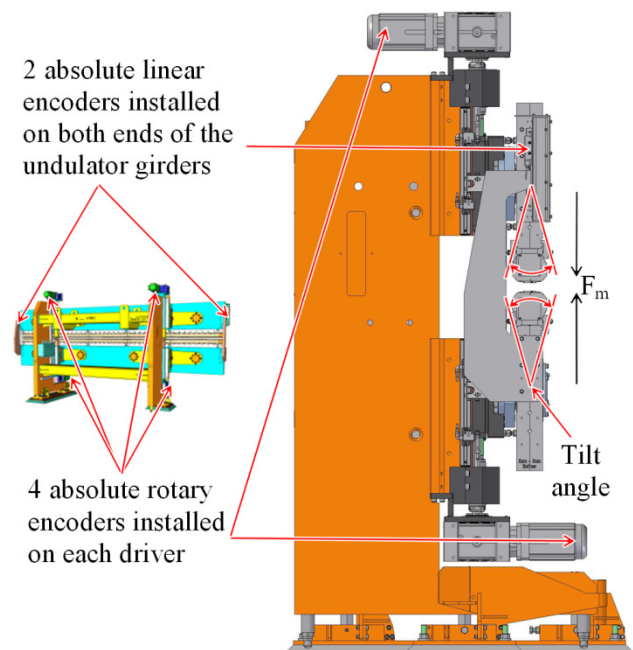


Figure 1: Undulator control and adjustment components.

The installation of a profiled linear guideway, which holds an encoder head, has to be validated in order to ensure the requirements of the gap measurement accuracy [1, 2] in the full operational range. For this purpose, two HEIDENHAIN MT 101K reference gauges, are mounted next to the linear encoders and are used to verify the adjustment quality. In order to automate this task, a C++ program was developed. It communicates with the undulator control system and adjusts the undulator gaps from a configuration file using the feedback from rotary encoders. As soon as the desired gap is reached, it reads the position of the linear encoders and the reference gauges. The gaps from the reference gauges are obtained via an HEIDENHAIN ND 287 readout device equipped with an Ethernet interface. Gap values are read from the configuration file and adjusted one by one. Hysteresis effects are identified by increasing and decreasing the gap.

the measurements, the program calculates the maximal hysteresis as well as the deviation between encoders and gauges. The prompt results are indicated by signal lamps. The measurement results are shown in graphical form to facilitate the search for the problems. If the results are out of specs, the adjustment procedure must be repeated. Otherwise, the measurement results can be saved in the form of PDF protocol.

ADJUSTMENT OF THE TILT ANGLE OF THE UNDULATOR GIRDERS

The magnet girders of an undulator have a rotational degree of freedom. Due to magnetic forces between the upper and lower magnet structures, the frame of an undulator bends and the girder tilt angle changes as a function of the gap. To minimize the influence of the horizontal component of the magnetic field, the girder tilt should be adjusted symmetrically around the vertical position over the full operational range of the gap (see Fig. 1).

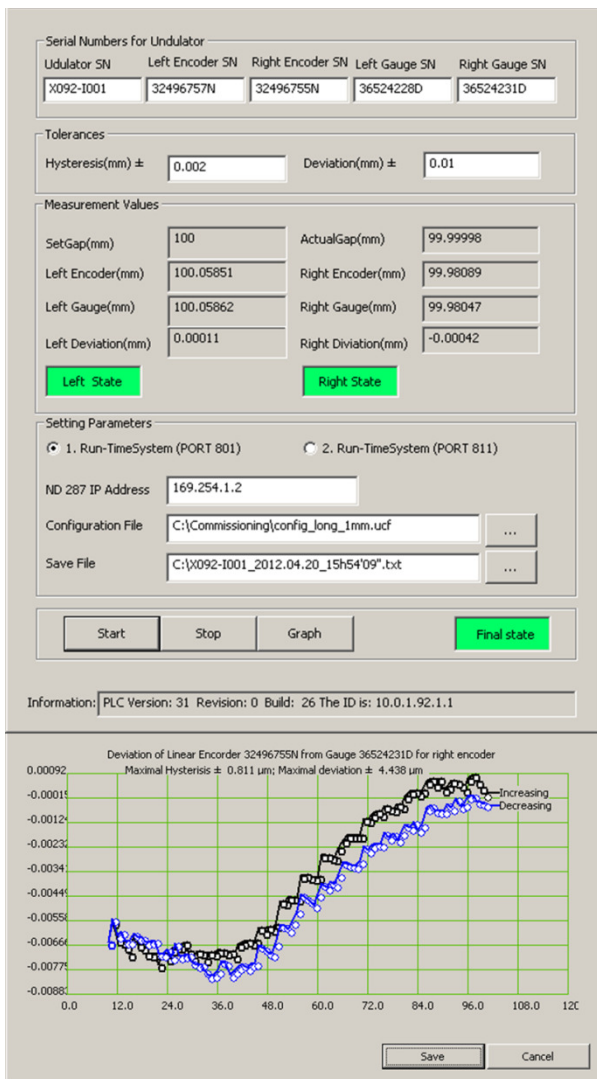


Figure 2: Main user interface and measurement results of linear encoder adjustment program.

A small hysteresis of about 1-1.5 μm in total between increase and decrease of the gap is seen in Fig. 2. After

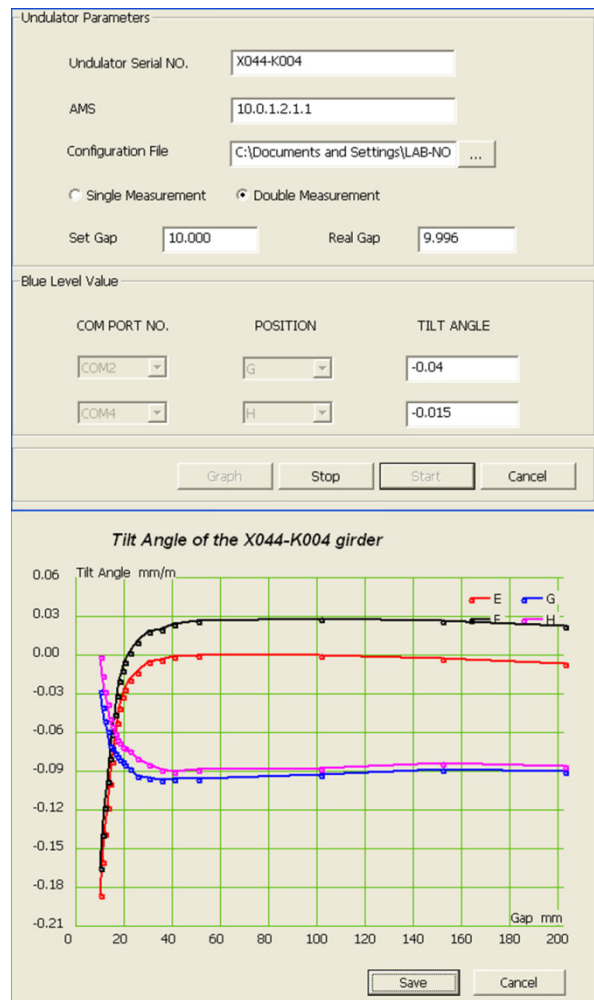


Figure 3: User interface and measurement results of girder tilt adjustment program.

A residual girder tilt of about ±200 μrad is permitted. Tilt measurements are made on one girder at a time. Two

WYLER BlueLEVEL devices are used on two reference surfaces. For precise adjustment, this procedure needs to be repeated several times, and this turned out to be time consuming.

As in the previous case, an automated measurement program tool based on C++ was created. The program runs on a separate PC. This computer, using one of its interfaces, is connected to BlueLEVEL instruments via a COM port to read the tilt values. Via Ethernet interface, it is connected to the Beckhoff industrial PC. Communication is established using the TwinCAT ADS library. The program sequentially changes the gap value and reads the tilt angle of the girder. The results of the measurements are presented in graphical form and can be saved as a PDF document.

EVALUATION OF THE FEEDFORWARD CORRECTION COEFFICIENTS

When gaps are small and the magnetic field is strong, the magnetic force between the girders of an XFEL undulator reaches up to 170 kN and causes a significant elastic deformation of the undulator support frame.

Deviation between the linear and the rotary encoder readings results may reach 500 - 900 μm. The linear encoder measures the true gap, while the rotary encoder reading needs to be corrected for the deformation effects.

First, the linear encoders must be adjusted and validated against the reference gauges, readings of which are considered “true” gap values. Second, the deviation is measured in the operational gap range. Third, parameters of an appropriate fit function are calculated. Fourth, the fit function with its parameters is transferred to and used by the undulator PLC for feedforward correction. This is a standard feature in the Beckhoff Numerical Control package.

Fitting Algorithm

The Gauss–Newton least-squares algorithm was used to fit the nonlinear function $f(\mathbf{c}, x)$ with parameters $\mathbf{c} = (c_1, c_2, \dots, c_n)$ to the measured data $(x_i, y_i) (i = 1, 2, \dots, m)$. This algorithm minimizes the sum of squares R of residual errors $r_i = f(\mathbf{c}, x_i) - y_i$. $R = \sum_{i=0}^n [f(\mathbf{c}, x_i) - y_i]^2$. Minimum is achieved when

$$\frac{\partial R}{\partial c_j} = 2 \sum_i r_i \frac{\partial r_i}{\partial c_j} = 0 \quad (j = 1, \dots, n)$$

The derivatives $\frac{\partial r_i}{\partial c_j}$ are functions of the independent variable and the parameters; therefore, these gradient equations do not have a closed form solution. An initial guess value $\mathbf{c}_j(0)$ must be substituted for the parameters. Afterwards, the parameters are processed iteratively, that is, the values are obtained by successive approximations: $c_j \approx c_j(k + 1) = c_j(k) + \delta c_j$, where k is iteration number and $\delta \mathbf{c}_j$ is a vector of increments. Using first-order Taylor approximation of $f(\mathbf{c}, x)$ at $\mathbf{c}_j(0)$ results in

$$\begin{aligned} f(\tilde{\mathbf{c}}, x_i) &= f_0(\mathbf{c}, x_i) + \sum_j \left(\frac{\partial f_0(\mathbf{c}, x_i)}{\partial c_j} \right) \delta c_j \\ &= f_0(\mathbf{c}, x_i) + \sum_j J_{ij} \delta c_j \end{aligned}$$

The residuals then are given by $r_i = y_i - f_k(\mathbf{c}, x_i) - \sum_j J_{ij} \delta c_j = \Delta y_i - \sum_j J_{ij} \delta c_j$

To minimize R , the gradient equation is set to zero and solved for δc_j [3]. A fitting function of the form $f(\mathbf{c}, x) = c_1 + c_2 * e^{-\frac{(x-x_0)}{c_3}}$ was chosen and is used in the program

Program Performance

The program works in a fashion similar to the previous ones. It sequentially changes the undulator gap values, acquires the values of rotary and linear encoders, calculates the deviation values, fits the exponential decay function, and, finally, creates a file with the correction coefficients, which will be used later by the undulator PLC for feedforward correction of rotary encoders. Fig. 4 shows the control box and the graphic output created by the program.

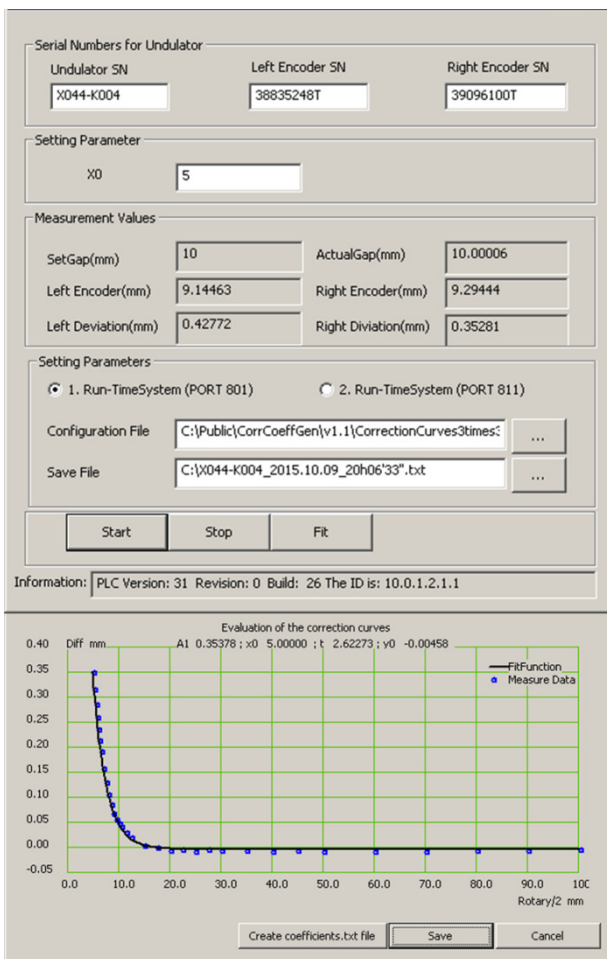


Figure 4: User interface and measurement results with fitting exponential decay function and evaluated coefficients.

CALIBRATION OF TEMPERATURE SENSORS FOR UNDULATOR CELL

NdFeB permanent magnet material is used for the XFEL undulators. The material has a reversible temperature coefficient η typically about $-1.1 \times 10^{-3}/^{\circ}\text{C}$. In order to compensate for the magnetic field change caused by temperature change, a correction of undulator gap is applied by the local control system. The gap correction Δg is calculated by the following equation: $\Delta g = \frac{\lambda_U \eta}{b + 2cg/\lambda_U} \Delta T$, where η is the temperature coefficient of the material, $\Delta T = T_{Nom} - T_{Act}$, T_{Nom} is the nominal temperature at which the K-parameter of an undulator has been measured, T_{Act} is the actual temperature of the magnet structures, λ_U is the undulator period length, g is the undulator gap, b and c are empirical constants, describing the gap dependence of the magnetic peak field. The threshold value for performing a change of the undulator gap is estimated to be between 0.05 and 0.2 °C. The accuracy of the temperature measurement system is envisioned to be 0.03 °C or better [4]. To provide accurate temperature measurements, three PT100-3 sensors are mounted on the magnetic structures. A fourth one is used for the vacuum chamber temperature control system. All four sensors need to be calibrated before usage.

Calibration Method

All four temperature sensors together with a certified reference temperature sensor are thermally connected to an aluminum block and inserted into a thermally stabilized water bath in a thermostat. To proceed with calibration measurements that would allow finding of the offset and slope at 0°C for calibrating sensors, the temperature thus could be well controlled.

In order to automate the calibration procedure, a C++ program runs on a separate computer. This computer is connected to the Beckhoff industrial PC via Ethernet and reads the data from the four undulator sensors. It is also connected via COM ports to the HAAKE water bath and to a certified ALMEMO temperature measurement device with the reference temperature sensor.

The program has two operating modes - calibration and monitor. In the calibration mode, the program sequentially changes the temperature of the water bath from the minimum to the maximum values in selectable steps. Once the set temperature is achieved and stabilized, it acquires the data from calibration and reference sensors and calculates the coefficients to be applied. Each sensor is equipped with a memory block, which allows saving the calibration coefficients. After evaluation of the offset and slope, the program can write these values directly into the memory block of the calibrated sensor. The results of the measurement could also be saved as a text file.

In the monitor mode, the program compares the data of 4 calibrated sensors with the data of 4 certified reference sensors which are mounted close to undulator and vacuum chamber sensors. In case it is necessary, new offsets to the sensors are applied. The program also saves

data into a text file. Fig. 5 shows the control box of the program.

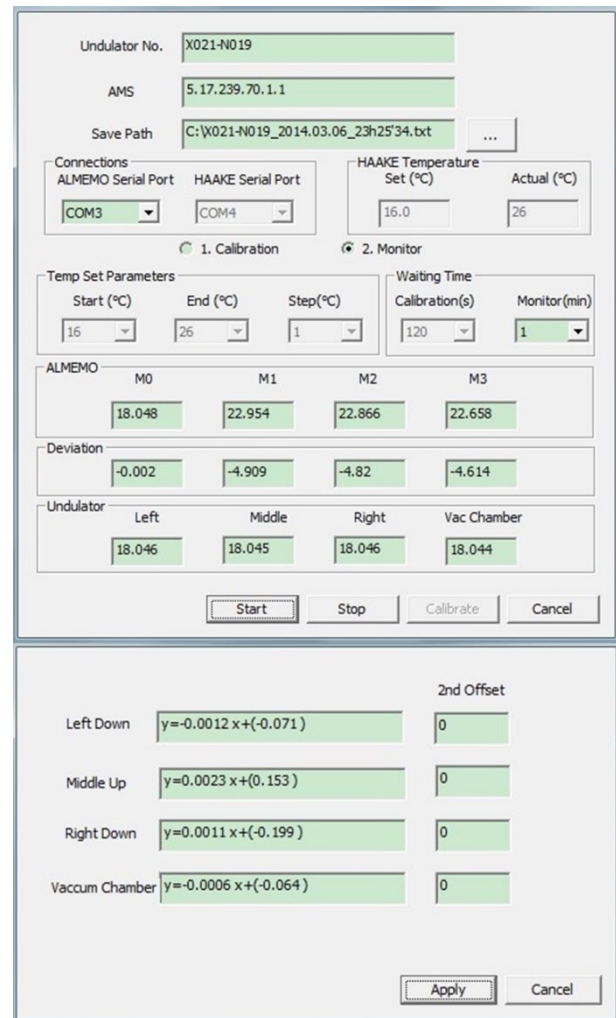


Figure 5: Main interface of the calibration program in monitor mode with evaluated coefficients.

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