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IMPLEMENTATION OF THE MOTION CONTROL SYSTEM FOR LCLS-II UNDULATORS

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Abstract

As part of the LCLS upgrade called LCLS-II, two new undulator lines were introduced: a soft X-Ray line (SXR) and a hard X-Ray line (HXR). Serving distinct purposes, the two undulator lines employ different undulator designs. The SXR line is composed of 21 vertical gap, horizontally polarizing undulators while the HXR line is composed of 32 undulator segments designed to operate on the horizontal axis and to produce a vertically polarized X-Ray beam. The HXR undulators will replace the LCLS ones and thus the control system was designed with the main goal of maximizing the re-utilization of existing hardware and software. For this purpose, the motion control system based on RTEMS running on VME with Animatics SmartMotors was developed as an upgrade of the LCLS design and the cam-based undulator girder positioning system has been reused. The all new SXR undulators employ a new control system design based on Aerotech motion controllers and EPICS soft IOCs (input-output controllers). This paper describes how the most challenging motion control requirements were implemented focusing on motion synchronization, K-value to gap transformation, cams kinematics and calibration, and user interaction.

INTRODUCTION

As part of the LCLS upgrade called LCLS-II, two new undulator lines were introduced: a Soft X-Ray line (SXR) and a Hard X-Ray line (HXR) [1]. The SXR line is composed of 21 vertical gap, horizontally polarizing undulators each paired with a downstream interspace assembly mounted on a separate support and a phase shifter. The HXR line is composed of 32 undulator segments designed to operate on the horizontal axis and to produce a vertically polarized X-ray beam [2, 3]. As for the soft line, each HXR undulator is paired with a phase shifter and an interspace assembly mounted on the same girder as the undulator. The drive system for the SXR undulators, an example of which is shown in Figure 1, consists of four Harmonic Drive servo motors with feedback from internal rotary encoders and two full-gap encoders attached at each end of the undulator segment. Brakes integrated with each motor allow holding the gap in position. The gap motion control is achieved for each undulator through a four axis Aerotech motion controller. The controller allows to drive the motors in a coordinated manner, supports safety features such as reacting to limit switches and ESTOP, and allows the measurement of the vacuum chamber position through linear potentiometers connected to its analog inputs.

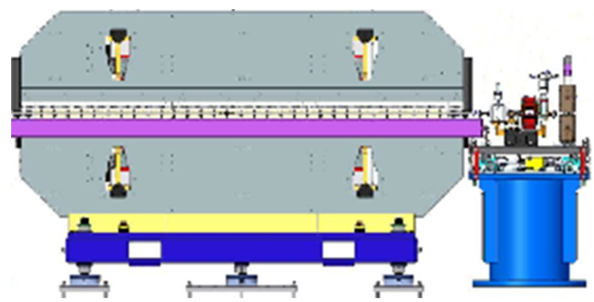

Figure 1: SXR undulator cell. Undulator and downstream interspace assembly.

Figure 2 shows a schematic representation of the EPICS IOC (input-output controller) developed to interface the controller with the accelerator distributed control system and other high-level applications (HLA).

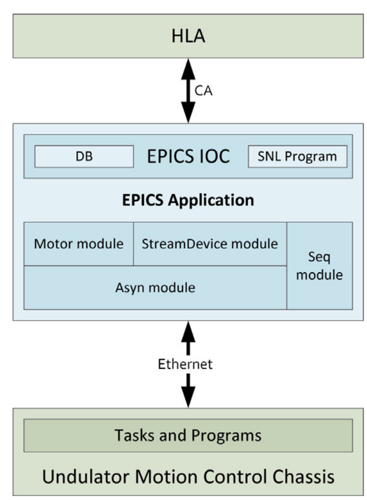

Figure 2: Structure of EPICS IOC for SXR undulators.

An SXR interspace assembly, shown downstream of the undulator in Figure 1, was designed to be inserted between consecutive undulator segments to provide a mounting surface for the vacuum assembly, Beam Position Monitors (BPM), quadrupole magnets, and a permanent magnet variable gap phase shifter. The top plate of the interspace assembly can be positioned independently of the undulator using a 5 Degrees-Of-Freedom (DOF) cam mover system driven by stepper motors to support beam based alignment and to allow repointing the undulator line. The gap of the phase shifter is controlled through a DC servomotor and an absolute linear encoder. A 6-axis Aerotech motion controller and an EPICS IOC structured similarly to the one used for the undulator are utilized for precise motion control of the interspace assembly.

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HXR undulators, a representation of which is shown in Figure 3, have been designed to replace the LCLS ones and thus the control system was designed with the main goal of maximizing the re-utilization of existing hardware and software. For this purpose, the motion control system based on RTEMS running on VME with Animatics SmartMotors was developed as an upgrade of the LCLS design. Its cam-based undulator girder positioning system has been reused.

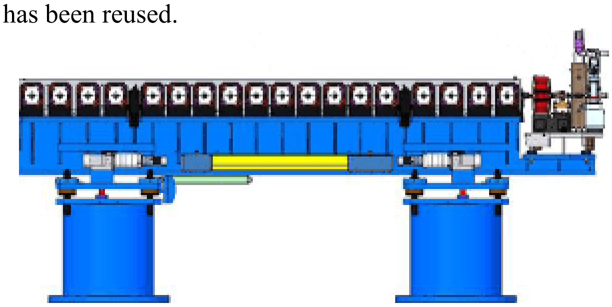

Figure 3: HXR Undulator cell. Undulator and downstream interspace cell.

Actuation of the gap control is achieved in HXR undulators through four Animatics SmartMotors with integrated brakes and incremental encoders. Additional absolute linear encoders are utilized for closed loop position control. An equivalent approach is also utilized to actuate the gap of the phase shifter mounted on the downstream interspace assembly. Ad-hoc electronics was designed to interface the limit switches and the ESTOP chain with the VME-based control system. Motion control and interfacing with the accelerator distributed control system is implemented through a crate with an MVME3100 single board computer running an EPICS IOC on RTEMS. The crate communicates with the hardware through Industry Pack (IP) cards on Acromag AVME-9760 carriers. Figure 4 is a diagram representing the structure of the IOC controlling the motion of the HXR undulator, cam movers, and phase shifter.

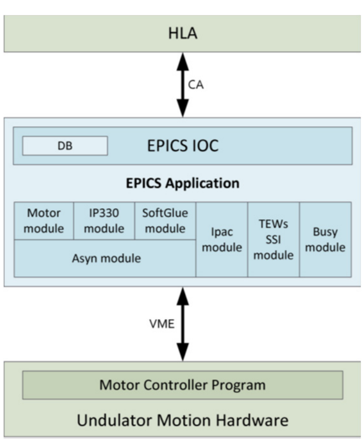

Figure 4: Schematic representation of the EPIC IOC running on VME controlling an HXR undulator, cam movers, and phase shifter.

Motion control requirements for the undulator lines were outlined in the Engineering Specification Documents (ESD). The remaining of this paper describes how the most relevant requirements were implemented using the hardware outlined in this section and in [2]. Last, an overview of the current installation status is given.

MOTION CONTROL SYSTEM

This section describes how some of the main features of the motion control system were implemented. Some features are specific to each undulator line while others, such as K vs Gap and girder kinematics are common among the two lines.

Tracking the Motion of the SXR Vacuum Chamber with the Undulator Gap

In the SXR undulator line, individual vacuum chamber segments are mounted on interspace assemblies and connected through flexible bellows. Interspace cam movers are then used to reposition the vacuum chamber segments during the beam-based alignment process. As the vacuum chamber is moved by consecutive interspace assemblies, the undulator centerline is required to remain centered on the vacuum chamber. In order to achieve this requirement, the undulator receives feedback of the vacuum chamber position through two linear potentiometers (Novotechnik-TR100), as shown in Figure 5, one mounted on the upstream end and one downstream.

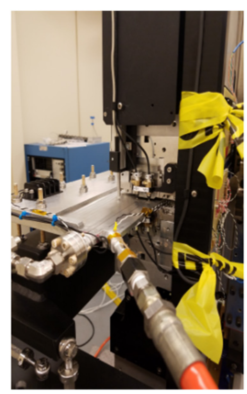

Figure 5: SXR Linear potentiometer in contact with the vacuum chamber.

Voltage from the linear potentiometers is acquired by the controllers of the two upstream motors. Aerotech ‘Autofocus’ functionality is then used to maintain the distance between the undulator jaws and the vacuum chamber as this is moved by the interspace cam movers. Tracking the motion of the vacuum chamber constitutes a second motion control requirement for the undulator line beyond the primary one of adjusting the undulator gap. The diagram in Figure 6 shows how the coordination between the two state sets was implemented.

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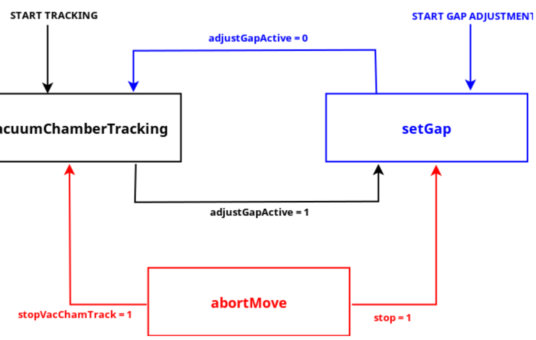

Figure 6: Schematic representation of the interaction between gap adjustment and vacuum chamber tracking state sets in SXR undulators.

Centering of the SXR Undulator Centerline on the Vacuum Chamber

Part of the vacuum chamber installation process is aligning it with the undulator gap set to 10 mm. This process ensures that the geometric center of the vacuum chamber is aligned with the magnetic axis of the undulator. When the undulator gap is adjusted, imperfections in the drive system cause the magnetic axis to shift up to 100 µm. This behavior was discovered during magnetic measurements of the undulators and a correction method that utilizes the linear potentiometers was implemented. The method is based on characterizing the linear relation that connects the potentiometer output voltage to the extension of the shaft. For the available linear potentiometers, the minimum voltage resolution is 1 mV which corresponds to 10 µm in shaft extension. An algorithm described by the following steps was implemented in EPICS to determine the offset and slope of the undulator centerline with respect to the vacuum chamber and correct for it.

- Calculate expected potentiometer extension as the difference between the current half gap and 5 mm (reference half gap); both upstream and downstream
- Calculate actual potentiometer extension based on potentiometer voltage and calibration data. Upstream and downstream
- Calculate centerline shift as the difference between the actual and expected potentiometer extension; both upstream and downstream.
- Combine upstream and downstream centerline shift to calculate overall centerline offset and slope; both upstream and downstream
- When selected by the user, control the undulator to compensate for the calculated centerline offset and slope.

As implemented, the method was implemented and verified by the SLAC Magnetic Measurement Facility (MMF) and it allows to reposition the undulator centerline with respect to the vacuum chamber with an error of less than 15 µm, RMS, which meets the 25 µm position accuracy requirement.

HXR Undulator Motion Control Loop Closure

Using the inherited VME-based architecture, the motion control loop for HXR undulators is closed at the EPICS level. In this setup, feedback is provided by two sets of absolute linear encoders: half gap and full gap. The four half gap encoders (Fagor SA-070-3**)** are mounted at the upstream and downstream end of each jaw and are used for initial gap positioning and controlling the symmetry of the jaws with respect to the undulator centerline. One full-gap encoder is mounted on the upstream end of the undulator and one downstream. These higher resolution encoders are used for fine positioning as, unlike the half gap encoders, they are not susceptible to mechanical deformations of the undulator jaws. While the half-gap encoders are always in use, the user can select to disable the full-gap encoders if rougher positioning is acceptable. If both encoders are selected, initial positioning is performed using half-gap encoders until the measured gap is within a user-specified dead band (25 µm). After that, target position calculation is performed using feedback from the full gap encoders in an iterative approach until the measured upstream and downstream gap is within the user-specified final dead band (0.25 µm).

All the encoders originally selected for the project can be read by a dedicated module on the VME. However, when performing the magnetic measurements of the first sets of production undulators it was discovered that the mechanical mounting and resolution of the SSI full-gap encoders could not provide the required position accuracy. New full-gap encoders that met the specifications (Renishaw RL26 series, 50 nm resolution) were selected and a new mechanical mounting system was designed. The new encoders utilize the BiSS-C communication protocol for which the available selected encoder read-out IP module has no support. In view of possible future upgrades of the undulator motion control system, a secondary motion controller was selected to read these encoders and provide the information for position control. The Delta Tau PowerPMAC Clipper was selected for this purpose, given its low cost, high flexibility, and modular hardware. Encoder readings from the PowerPMAC Clipper are exposed through PVs provided by a secondary EPICS. Soft IOC Safety features based on PV status were implemented to stop the motion if read back from the full-gap encoders is not available or is corrupted.

Calculation of the Undulator K Parameter Based on Gap

The K parameter measures the strength of an undulator and is closely related to the undulator gap. For Free Electron Laser (FEL) operation, the value of the K parameter required for each undulator along the line is specified with relative accuracy of 10-4 which corresponds to 1 µm accuracy in setting the gap of each undulator. The empirical relation between gap and value of the K parameter is highly nonlinear and is determined for each LCLS-II undulator during the magnetic calibration process.

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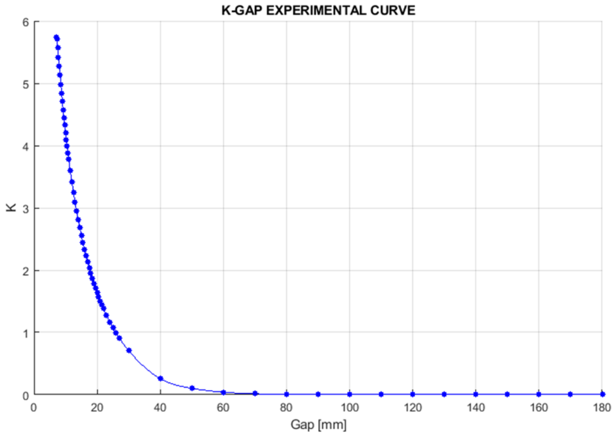

Figure 7: Plot of relation between undulator gap and K value.

The best approximation to determine analytically the required accuracy in relating undulator gap and K parameter is a third order spline as shown in Figure 7. A dedicated EPICS module was developed at SLAC to perform the direct and inverse transformation and convert the undulator gap into a value for the K parameter and vice-versa. The module was designed to parse a calibration file containing sets of measured gaps and corresponding K values and to populate the coefficients of the third order spline interpolation. This process is performed once, when the IOC is booted. During operation, upstream and downstream gap values are automatically converted into K values. Also, this allows the user to control the undulator by specifying a gap parameter which gets automatically converted into a desired gap value and transmitted to the motors. Methods were implemented to check the validity of the input data and to enable and disable the spline interpolation in case of invalid input. The relationship between the value of the undulator K parameter and its gap is also dependent on the ambient temperature. For this reason, Resistance Temperature Detectors (RTDs) were included in the undulator design. Undulator temperature .calculated by averaging the reading from available RTDs can be used to adjust the K-Gap relation based on the difference between the actual temperature and the temperature at which the undulator was characterized. The mathematical implementation of the transformation was successfully verified at the SLAC Magnetic Measurement Facility and was also ported to phase shifters where an analogous calculation is needed to relate the gap to the Phase Integral parameter.

Undulator Line Precise Positioning

The positioning system for both undulator lines is based on the concepts developed to position LCLS undulators [4]. The cam-based girder mover system developed for the LCLS undulators and shown in Figure 8 was re-used for the HXR undulators. A similar approach was developed for SXR interspaces. Both systems are composed of five actuators that provide allowing to move each HXR undulator segment and each HXR and SXR quadrupole in X, Y, roll, pitch, and yaw. The only constrained motion direction is along the beam axis Z.

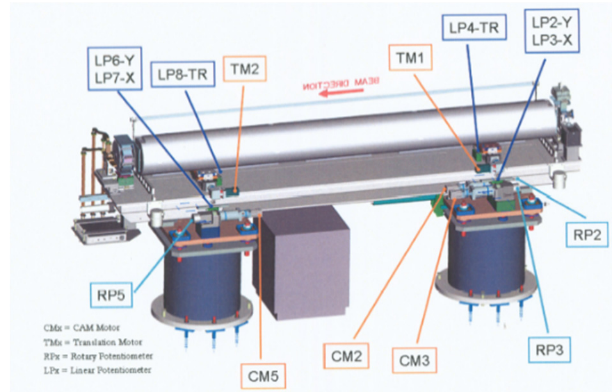

Figure 8: LCLS undulator cam movers.

HXR cams are controlled by Animatics SmartMotors providing 2000 steps/revolution coupled with a multi-stage harmonic drive reduction system providing a total reduction ratio of 4900:1. Because of the much lower load on the motors, SXR cam movers are driven by Applied Motion HT23-series DC stepper motors. Given the non-linear characteristic on cam-based motion, absolute feedback is provided by rotary potentiometers mounted on the shaft of each cam mover. The potentiometers utilized are P220 series from Novotechnik, U.S. and provide an angular resolution of 0.004°. Linear potentiometers (Novotechnik TR-10), are also utilized as secondary feedback to determine the measurement range and calibration offset of each rotary potentiometer. A script was developed to automatically move each cam mover through a full revolution, record the voltage from the associated rotary and linear potentiometer, and calculate the calibration parameters. Kinematic equations to determine the position of the undulator girder based on the cam angles were developed and implemented in EPICS.

MOTION CONTROL SYSTEM INSTALLATION AND COMMISSIONING

The magnetic properties of all SXR undulators and phase shifters have been measured and extensive testing of the motion control system has been performed. HXR undulators and phase shifters are also being magnetically characterized and the software is being tested extensively. Physical installation of the devices in the SLAC undulator hall, shown in Figure 9 has begun in mid-August 2019 and is proceeding at a steady pace of one undulator per day.

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Figure 9: SLAC undulator hall. SXR undulators are visible on the left. HXR undulators and still empty girders are visible on the right. Beam direction will be into the page.

The LCLS-II power and network infrastructure has been completed and the control system racks are being powered up and commissioned. A team of engineers and technicians is working daily to release the control system software, configure the controllers, and perform functional checkouts. Installation and control system deployment is expected to be concluded by December 2019 and beam based commissioning to start in January 2020.

CONCLUSION

This paper provided an overview of the implementation of the most relevant features of the motion control system for LCLS-II SXR and HXR undulators. Software and hardware have been extensively tested in the development test-stands and the commissioning of devices has begun and is proceeding at a steady pace. Future work will involve developing high level applications for coordinated control of each undulator line and upgrading the control system allow faster, simpler and more reliable motion control.

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