DESIGN AND INTEGRATION OF MOTION CONTROL FOR THE IUT24 IN-VACUUM UNDULATOR AT TPS

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Abstract

The In-Vacuum Tapered Undulator (IUT24) was developed for the Phase-III beamline project at the Taiwan Photon Source (TPS). To counteract strong, non-linear magnetic attraction forces while maintaining precise synchronization between magnet arrays, a robust motion control architecture was implemented. This system integrates an EPICS-based supervisory layer with EtherCAT field I/O and BiSS-C absolute linear encoders (50 nm resolution) in a closed-loop pulse-command configuration. Experimental results demonstrate that during dynamic gap transitions, the tracking error is strictly maintained within ± 2.5 µm, and inter-axial synchronization remains within 0.5 µm. Furthermore, long-term position stability was measured at ±150 nm over 200 minutes. This paper details the hardware integration, advanced motion control strategies, and comprehensive performance evaluations that confirm the system's readiness for high-precision beamline operations.

INTRODUCTION

The Taiwan Photon Source (TPS) is adding new beamlines through the Phase-III project [1]. One of the devices introduced in this program is the IUT24 in-vacuum undulator, which was integrated into the storage ring in 2026. Its magnetic field is set by adjusting the gap between two opposing magnet arrays over a range of 5–25 mm. Compared with a conventional out-of-vacuum device, an in-vacuum undulator places tighter demands on the motion system because vacuum loading and magnetic force both act directly on the mechanism. The controller must therefore provide fine positioning and keep the two drive axes synchronized during gap tuning and tapering. This paper describes the hardware layout, the control scheme, and the test results obtained on the IUT24 platform before routine operation.

SYSTEM HARDWARE ARCHITECTURE

The control system for the IUT24 in-vacuum undulator is constructed around a distributed heterogeneous network architecture designed to balance high-precision motion execution with robust peripheral monitoring. A Linux-based industrial PC, specifically the ADLINK MXC-6300 series, functions as the EPICS Input/Output Controller (IOC) [2] to manage high-level process variables and interface with the broader beamline control network via an EPICS gateway. For real-time operations, a Galil DMC-4040 multi-axis controller handles trajectory generation and high-speed close loop regulation [3], communicating with the IOC through a private UDP link that supports state updates at rates up to 100 Hz. Complementing this, peripheral instrumentation such as vacuum gauges and corrector power supplies are integrated using the EtherCAT protocol (IEC 61158), which reduces wiring complexity and provides the deterministic communication required for synchronized operation. [4]

The systemic integration of the IUT24 control framework is illustrated in the hardware architecture diagram (see Fig. 1), which emphasizes a modular, three-tier topology consisting of the supervisory EPICS layer, the real-time motion control core, and the distributed fieldbus. At the supervisory level, an industrial PC acts as the EPICS Input/Output Controller (IOC), orchestrating data exchange between the beamline control Ethernet and the underlying motion hardware. The real-time layer centers on a multi-axis motion controller that receives feedback from BiSS-C (Bidirectional/Serial/Synchronous-Continuous) absolute linear encoders through specialized wiring adapters to ensure nanometer-scale positioning resolution. Simultaneously, an EtherCAT-based fieldbus manages auxiliary subsystems, including vacuum gauges and temperature-monitoring RTD sensors, ensuring that environmental parameters are digitized and synchronized with the motion state.

The physical implementation of this architecture is realized through a dual-rack configuration, as shown in the installed hardware assembly (see Fig. 2), which is designed to isolate sensitive control signals from high-power vacuum and magnet electronics. The primary Motion Control Rack consolidates the EPICS IOC, the trajectory-generation controller, and high-performance motor drivers, utilizing custom hardware protection boards to handle limit-switch and emergency-stop interlocks. In contrast, the Vacuum and Power Supply Rack houses the ion-pump controllers, Bayard-Alpert (BA) gauge controllers, and correction-magnet power supplies. This spatial decoupling serves a dual purpose: it significantly reduces electromagnetic interference (EMI) across the feedback loop and streamlines maintenance protocols by separating the core drive mechanics from the vacuum support infrastructure.

Protection of the vacuum chamber and magnet arrays is implemented at several levels. Software limits in the EPICS motor record block invalid user commands, while the Galil controller monitors the following error and aborts motion when it exceeds 0.05 mm. Hardware interlocks, including limit switches and torque-limit sensors, are wired directly to the motor-driver inhibit pins to prevent collision even if network communication is lost.

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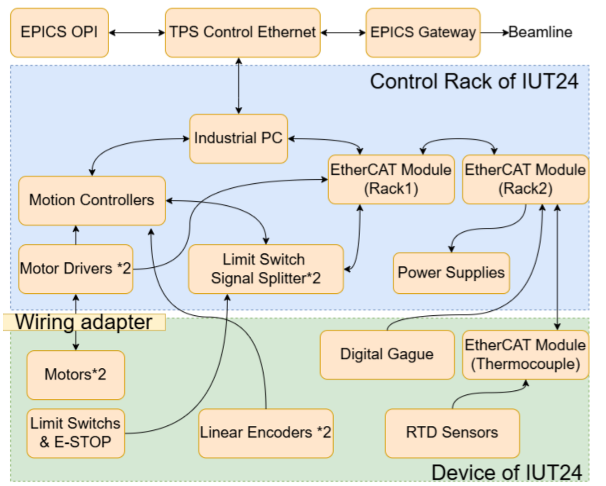

Figure 1: Hardware architecture of the IUT24 control system.

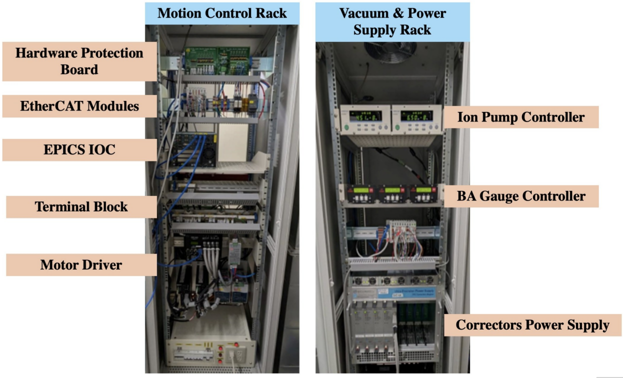

Figure 2: Installed motion-control rack and vacuum/power-support rack of the IUT24 system.

Mechanical Drive System and Resolution Analysis

The mechanical transmission was designed to provide enough torque margin for stable gap motion [5]. Each axis is driven through a 1:10 planetary gearbox followed by a 1:50 worm reducer, giving a total reduction ratio of 1:500. With a 10 mm ball-screw pitch, the corresponding gap change per motor revolution during symmetric two-side motion is

$$\text{Gap change} = \frac{10\ \text{mm}}{500} \times 2 = 40\ \mu\text{m}/\text{rev}.$$

This reduction ratio is sufficient to overcome the magnetic attraction force while maintaining stable holding torque at the target gap. The dual-side drive arrangement is shown in Fig. 3.

CONTROL SOFTWARE ARCHITECTURE

IUT24 uses two motors for gap control. Motion state, limit-switch status, alarms, and encoder readings are updated from the motion controller through a private UDP link at rates up to 100 Hz. The digital and analog interfaces required for corrector power supplies, gauge readback, and temperature monitoring are implemented with EtherCAT, standardized in IEC 61158 [6]. The EtherCAT support was adapted from the EPICS interface developed at Diamond Light Source for the IgH EtherCAT master [7] and then adjusted for the Beckhoff modules used in IUT24, following the control approach previously applied to TPS insertion devices [8].

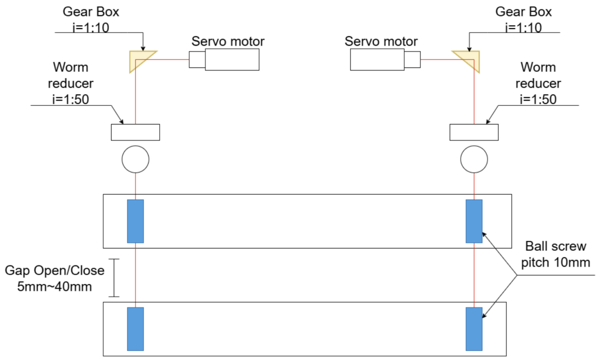

Figure 3: Mechanical transmission arrangement for the IUT24 gap drive.

ADVANCED CONTROL STRATEGY

Closed-Loop Stepper (CLS) and BiSS-C Feedback

The IUT24 drive uses a closed-loop pulse-command architecture. Although servo motors are used, the motor amplifiers accept pulse/direction commands, and the linear encoders close the outer position loop. This arrangement avoids position loss under the varying magnetic load seen during gap adjustment.

Multi-Parameter Loop Tuning

To reduce tracking error during tapering, where the two ends of the undulator move to different gaps, three parameters were tuned in the control loop. The proportional gain (KP) sets the loop stiffness. The velocity feed-forward term (FV) reduces error during constant-speed motion, and the acceleration feed-forward term (FA) compensates for the inertia of the 1:500 transmission system.

Figure 4 depicts the feedback loop between the Galil controller and the optical linear encoders. By using the BiSS-C protocol, the system achieves high-speed bidirectional communication. The controller computes the position error between the commanded and encoder positions and applies proportional and feed-forward terms to track the motion profile.

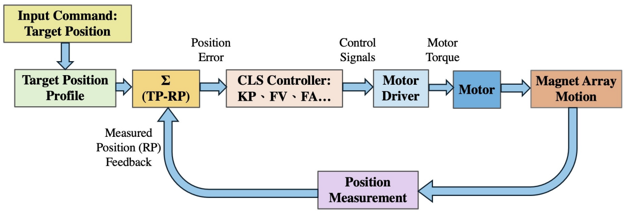

Figure 4: Schematic of the Closed-Loop Stepper (CLS) control logic.

PERFORMANCE EVALUATION OF THE MOTION CONTROL SYSTEM

The performance of the IUT24 (In-vacuum Undulator) motion control system was evaluated across three critical dimensions: dynamic trajectory tracking, micro-stepping resolution, and long-term stability. The dynamic response of the system during a gap transition from 25 mm to 5 mm is illustrated in Fig. 5. Utilizing a trapezoidal velocity profile, the experimental results demonstrate that the following errors for both the upstream and downstream axes are strictly maintained within ±2.5 µm. Furthermore, the synchronization between the two axes, represented by the Taper of Gap Motion, remains within a narrow range of ±0.5 µm. This indicates that the control algorithm effectively suppresses axial asymmetry during high-speed movement, ensuring the structural symmetry and stability of the magnetic field during gap adjustments.

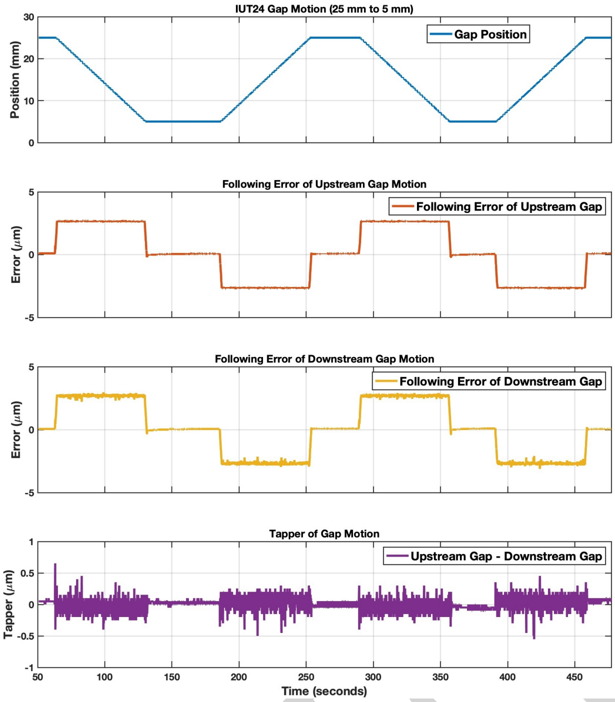

Figure 5: Dynamic tracking performance of the IUT24 gap motion from 25 mm to 5 mm. The plots illustrate the following errors for both upstream and downstream axes, along with the inter-axial synchronization error (taper) maintained within ±0.5 µm.

To verify the system's capability for fine energy tuning, a micro-stepping test was conducted near the 5 mm gap position, as shown in Fig. 6. The results confirm a high-precision positioning resolution of 1 µm. The observed staircase-like displacement curve reveals rapid settling times with negligible overshoot or oscillation. This performance suggests that the closed-loop control parameters are optimally tuned to meet the stringent requirements for photon energy calibration at the beamline station.

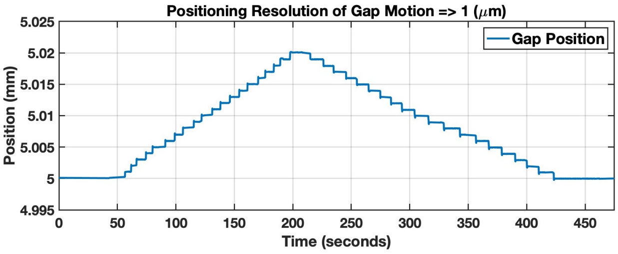

Figure 6: Positioning resolution test demonstrating the 1 µm micro-stepping capability of the gap motion system, showing precise step response and rapid settling at the 5 mm gap position.

Long-term stability monitoring at the minimum gap of 5 mm, as shown in Fig. 7, revealed that the position deviation remained within a minute range of ±0.15 µm (150 nm) over a 200-minute duration. This exceptional stability is highly consistent with the system's hardware specifications, specifically the 50 nm resolution of the linear encoders; the observed fluctuations represent only a few increments of the quantization noise floor. By effectively suppressing environmental thermal drift and mechanical vibrations, these results confirm that the IUT24 system provides a highly consistent and reliable radiation source for prolonged synchrotron radiation experiments.

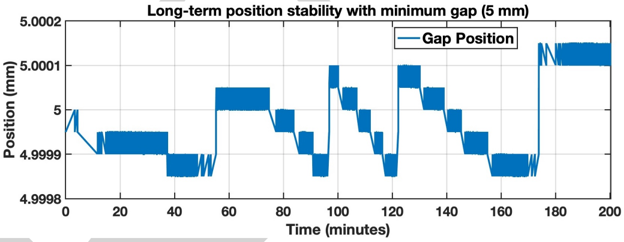

Figure 7: Long-term position stability monitoring at the minimum gap of 5 mm over a 200-minute duration. The position deviation remains within ±150 nm, consistent with the 50 nm resolution of the linear encoders and environmental noise floor.

CONCLUSION

The IUT24 motion-control testbed successfully demonstrates the seamless integration of an EPICS-based control layer, EtherCAT-based diagnostics, and a high-speed closed-loop stepper scheme. Under significant magnetic loading, the system achieved a dynamic tracking error of less than ± 2.5 µm and a positioning resolution of 1 µm, fulfilling the stringent requirements of TPS Phase-III beamlines. Notably, the implementation of 50 nm resolution linear encoders enabled a long-term gap stability of ± 150 nm, with fluctuations effectively limited to the quantization noise floor. This architecture not only validates the current IUT24 performance but also establishes a high-performance, standardized baseline for future undulator control systems at the TPS.

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