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DESIGN OF BEAM COLLIMATOR CONTROL SYSTEM FOR HEPS

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Abstract

The collimator for the High Energy Photon Source (HEPS) primarily intercepts lost particles caused by the Touschek effect, reducing beam losses in non-target areas, and serves as a dump station for equipment protection during emergencies. Utilizing EtherCAT industrial Ethernet technology ensures precise control, while LVDT sensors are employed for position calibration due to the intense radiation environment. The system incorporates multiple layers of safety protection, including software limits, mechanical limit switches, and emergency stop switches. Remote control is achieved through an EPICS architecture with communication between the EPICS IOC and the system via MODBUS TCP protocol. System testing indicates that the collimator achieves a repeatability precision of ±0.01 mm, validated the reliability and accuracy of the system.

INTRODUCTION

The High Energy Photon Source (HEPS) is one of the key construction projects during China's 13th Five-Year Plan, dedicated to providing high-quality synchrotron radiation to support cutting-edge scientific research. The design and implementation of the collimators are crucial for enhancing the overall performance of HEPS. HEPS is equipped with four collimators located at the R03, R15, R27, and R39 units of the storage ring. Each collimator consists of two independent stages driven by motors to achieve high-precision automatic horizontal adjustment, with a required repeatability of position ≤0.02 mm, and the capability to operate reliably in a high-radiation environment. The actual installation of the collimator in HEPS storage ring is shown in Figure 1.

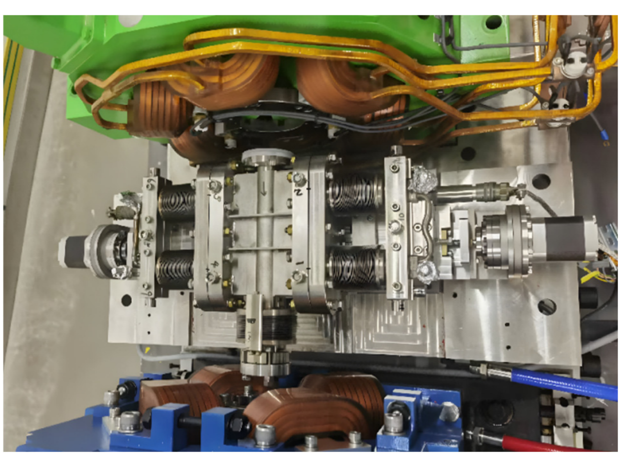

Figure 1: A collimator in HEPS storage ring.

SYSTEM DESIGN

EtherCAT Control Architecture

The EtherCAT control architecture employs a distributed system design based on EtherCAT industrial Ethernet bus technology, leveraging its capabilities for high-speed data transmission and high-precision synchronization to ensure precise control of the collimator [1]. The system consists of a master station and multiple slave stations, where the master station is responsible for issuing control commands and collecting feedback information; the slave stations include drive units for stepping motors and I/O modules for sensor signal acquisition. The schematic diagram of the EtherCAT architecture for the collimator control system is presented in Figure 2.

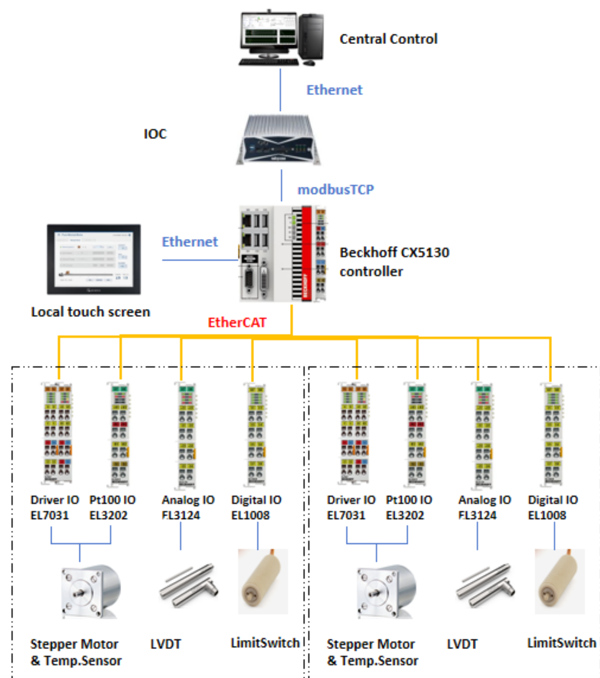

Figure 2: EtherCAT control architecture of collimator.

- Master Controller: A Beckhoff CX5130 embedded controller equipped with licensing for 10-axis drives and supporting the MODBUS/TCP protocol.
- Stepper Motor Driver: The Beckhoff EL7031 stepper motor driver, capable of driving stepper motors with high microstepping ability, achieving a resolution of 64 microsteps.
- Stepper Motor: Radiation-resistant stepper motors from AML UK, model D42.2, with a step angle of 1.8°.

The lead screw pitch of the stage is 5 mm, resulting in a calculated motion resolution of 0.08 micrometers. With this design, the system achieves high-precision motion

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control, meeting the accuracy requirements of the collimator.

The slave stations of the system also include the Beckhoff analog input module EL3124 for receiving LVDT signals and the Beckhoff digital input module EL1008 for receiving limit switch signals, among other components.

Absolute Position Calibration

In standard motion control systems, absolute linear encoders are commonly utilized to provide high-precision position measurements. However, in the high-radiation environment where the HEPS collimator is located, electronic components such as encoders cannot function reliably. Consequently, this system adopts an LVDT (Linear Variable Differential Transformer) as an alternative solution to achieve high-precision absolute positioning [2].

The ABEK FHNA19 model LVDT sensor is employed, which is capable of withstanding a maximum irradiation dose of 1e6 Gy, has a measurement range of ±25 millimeters, and offers a repeatability precision of 2.5 micrometers.

Position Calibration Process: after installing the LVDT sensor, initial calibration is conducted to record the offset between the LVDT's zero point and the actual zero point of the collimator. Thereafter, the position signals generated by the LVDT are transmitted over the EtherCAT bus to the master controller (CX5130), where appropriate compensation is applied in the control software to ensure real-time positional accuracy. Through the implementation of the LVDT sensor, the system not only facilitates real-time monitoring of the collimator's position but also ensures precise adjustments can be made as required, maintaining the collimator in its optimal operational position.

Safety System Design

To ensure the safety of the collimator control system during operation, a multi-level safety protection system has been implemented, primarily comprising software limits, mechanical limit switches, and emergency stop button.

Software Limits: The system is configured with software limit thresholds. If the position of the collimator exceeds these predefined limits, the software will automatically prohibit further motor movement, preventing equipment damage or safety incidents caused by operational errors.

Mechanical Limit Switches: Mechanical limit switches are installed at both ends of the collimator stage. When the stage contacts the limit switch, the motor immediately ceases unidirectional movement, preventing overtravel beyond physical boundaries.

Emergency Stop Switch: An emergency stop button is mounted on the control cabinet. Upon activation of the emergency stop button, the system promptly cuts off power to the motor, ensuring that all moving parts cease operation rapidly in emergency situations, safeguarding operator safety.

Through these multi-level safety measures, the system not only effectively prevents safety accidents caused by improper operations but also responds promptly in emergencies, ensuring the safety of personnel and equipment.

EPICS Remote Control

To achieve remote control and monitoring of the collimator, the system employs the EPICS architecture [3]. EPICS provides a rich set of tools and protocols that support the development and integration of distributed control systems. Communication between the Beckhoff PLC and the EPICS IOC utilizes the MODBUS/TCP protocol, ensuring stable data exchange.

The design of the EPICS IOC is a critical component of this implementation, involving the following steps:

- Environmental Preparation: Install Debian operating system and install the necessary software packages.
- EPICS Installation: Set up environment variables, install EPICS Base, and configure relevant modules.
- MODBUS Installation: Install the MODBUS module, configure related environment variables, and compile it.
- IOC Configuration: Define database records for the EPICS IOC and write the MODBUS protocol files.
- IOC Startup: Configure the IOC startup script to ensure proper communication between the MODBUS server and the EPICS IOC.

Below is a sample of the key code for obtaining the current axis position:

- record file code

```
record(ai, "R03CLM:Axis1_CurrentPosition")
 {
   field(DTYP, "asynIPPort")
   field(INP,    @R03CLM.proto:Axis1_CurrentPosition")
   field(SCAN, "Passive")
 }
```

- # template file code

```
file "../../db/aiFloat64.template" { pattern
{ P, R, PORT, OFFSET, DATA_TYPE, LOPR, HOPR, PREC, SCAN}
{ R03CLM:, Axis1_CurrentPosition, AI1_FLOAT, 2, FLOAT32_LE, -1e6, 1e6, 4, "I/O Intr"}}
```

The EPICS OPI interface is developed using Phoebus CSS, as illustrated in Figure 3.

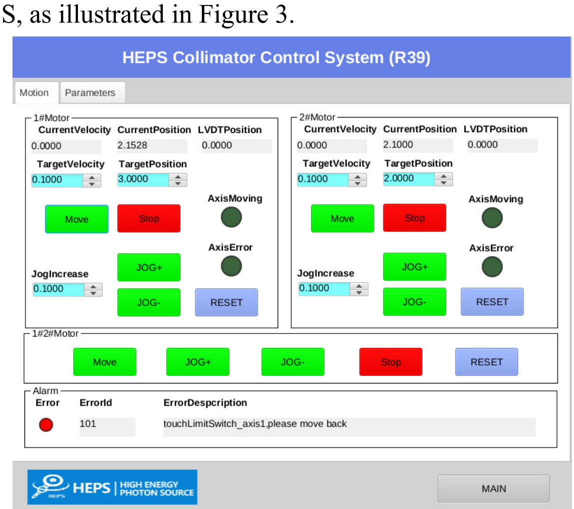

Figure 3: Remote control OPI using phoebus CSS.

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SYSTEM TEST

To verify the motion precision of the collimator control system, tests were conducted using a MITUTOYO digital micrometer gauge with a resolution of 1 micron and an accuracy of 2 microns. By performing repeated measurements at several critical positions on the collimator, the reliability of the test data was ensured. The test results indicated that the repeatability precision of the collimator reached ±0.01 millimeter, meeting the technical specification requirements. The measurement process is illustrated in Figure 4.

Figure 4: Precision measurement.

The comparison of technical specifications and measured value for the collimator control system is shown in Table 1.

Table 1: Technical Specification and Measured Value

Technical Specification	**Specified Value** [mm]	**Measured value** [mm]
Repeatability Precision	0.02	0.01

CONCLUSION

By adopting EtherCAT bus technology and the EPICS architecture, efficient remote control of the collimator has been realized. The motion precision of the system was verified through repeated measurements using a MITUTOYO digital micrometer gauge. Test results indicated that the repeatability precision of the collimator achieved ±0.01 millimeters, meeting the design requirements. The high precision and reliability of the system have been fully validated, ensuring stable operation within the High Energy Photon Source (HEPS).

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