Bluesky Control Software for Deposition Laboratory at NSLS-II

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Abstract

At Brookhaven National Laboratory's National Synchrotron Light Source II (NSLS-II), the Experimental Development (ED) Program advances synchrotron science and technology by developing new X-ray technologies for the broader scientific community. Central to the ED Program is the Deposition Laboratory, which focuses on creating world-class nanofocusing optics and providing thin-film deposition capabilities essential for NSLS-II beamlines. These activities revolve around operating a custom-designed large deposition chamber. The chamber's original control software, developed in-house between 2009 and 2010, has become outdated and is incompatible with EPICS (Experimental Physics and Industrial Control System), the standard control framework at NSLS-II. This report outlines the collaborative effort between the ED and Data Science and Systems Integration (DSSI) Programs to modernize the chamber's control software, making it fully EPICS-compatible and integrating it with Bluesky for advanced data acquisition and experiment orchestration.

Introduction

The Deposition Laboratory at NSLS-II plays a critical role in the ED Program by enabling advanced thin-film deposition and nanofocusing optics development. At the heart of this lab lies a custom-designed deposition chamber, essential for producing precision optics required by NSLS-II beamlines. Historically, the chamber's control software was developed as a standalone system without consideration for modern frameworks like EPICS. EPICS, widely used in accelerator facilities, provides a standardized infrastructure for integrating hardware devices such as motors, sensors, and controllers into a cohesive system. Its incompatibility with the legacy software has posed significant challenges, including limited maintainability and reliance on a single developer. The modernization project seeks to resolve these challenges by aligning the control system with EPICS standards and leveraging Python-based tools such as Ophyd and Bluesky. Ophyd simplifies interaction with EPICS IOCs (Input/Output Controllers), while Bluesky orchestrates experiment planning, execution, and data acquisition. Together, these frameworks offer a robust and extensible solution for laboratory automation, allowing the chamber to meet evolving scientific needs.

Methods

Control System Architecture:

The upgraded control system integrates EPICS IOCs, which serve as the foundational layer, managing direct hardware interactions. Each IOC corresponds to a specific hardware component, such as a motor or sensor, enabling precise control and monitoring. This foundational layer was developed in consultation with the NSLS-II engineering team to ensure compatibility with existing infrastructure and adherence to facility standards.

On top of this layer, Ophyd provides a Pythonic abstraction, allowing developers and researchers to interact with hardware using high-level APIs. This abstraction greatly simplifies the process of integrating new devices or updating existing configurations. For instance, Ophyd allowed us to create standardized device objects that encapsulate the chamber’s hardware elements, streamlining the process of writing scripts and reducing error-prone manual configurations.

Bluesky, acting as the orchestration layer, enables researchers to define experimental workflows through a combination of Python scripts and a graphical user interface (GUI). The GUI, connected to a Bluesky Queue Server, allows real-time submission and monitoring of experiment plans. Additionally, a command-line interface (CLI) supports advanced users who prefer scripting for automation and debugging.

To ensure compatibility and reliability, Dockerized EPICS environments were employed during development. This approach allowed for consistent testing and debugging of IOCs across multiple hardware configurations. The use of version-controlled Python environments further ensured reproducibility and streamlined collaboration among team members.

Deposition Chamber Use in Beamline Research:

The deposition chamber is a pivotal tool in synchrotron-based research, enabling the precise application of thin films onto substrates. These films are critical for fabricating optical components such as mirrors and lenses used in beamlines to focus and direct X-rays. The chamber's vacuum environment and magnetron sputtering technology ensure uniform deposition of materials, essential for achieving the high precision required in nanofocusing optics.

The chamber's operation involves multiple subsystems, including:

1. Vacuum Systems: Ensures the controlled environment necessary for high-purity deposition.
2. Target Manipulation: Allows precise positioning of deposition materials.
3. Sputtering Sources: Magnetron sputtering technology used to apply thin films.
4. Sensors and Monitors: Real-time tracking of deposition rates, thickness, and environmental conditions.

Each subsystem was integrated into the EPICS framework through custom-developed IOCs, enabling centralized control and monitoring. For example, the magnetron sputtering sources required real-time adjustments to power levels based on sensor feedback, a task now automated through EPICS and Bluesky integration.

Data Acquisition and Automation:

Data acquisition and automation are at the core of the redesigned system. The new control software leverages Bluesky's data acquisition capabilities, providing seamless integration with NSLS-II's data management infrastructure. Custom Python scripts, previously developed to automate long-duration experiments, were refactored to work within the Bluesky framework. This integration allows for real-time data logging, visualization, and alert generation, ensuring that researchers can monitor and adjust experiments dynamically. For instance, a 15-day experiment involved dynamically adjusting sputtering parameters based on real-time sensor feedback. Bluesky's RunEngine was used to orchestrate this process, enabling continuous data capture and automated adjustments without manual intervention. These capabilities drastically reduced the time required for experiment supervision while improving data quality.

Results

The modernization project achieved several critical milestones, addressing long-standing limitations in the deposition chamber's legacy software. The development of an EPICS-compatible control system unified previously disparate subsystems under a single framework, significantly improving both usability and maintainability. This new system integrates key subsystems, including vacuum controls, target manipulation, sputtering sources, and sensors, into a centralized platform. The modular design facilitates future upgrades, ensuring the chamber's continued relevance in cutting-edge research.

One notable accomplishment was the integration of Ophyd and Bluesky frameworks, which streamlined experiment planning and execution. Ophyd's Pythonic abstraction of EPICS IOCs simplified device integration and reduced the complexity of hardware configurations. Bluesky further enabled efficient orchestration of experimental workflows, supporting advanced features such as conditional logic and looping. These capabilities drastically reduced the need for manual intervention, allowing researchers to focus on analysis and interpretation rather than system management.

Comprehensive testing on simulated hardware validated the system's robustness. During beta testing, the software successfully handled asynchronous task execution, ensuring continuous operation even during complex workflows. The inclusion of Docker environments and version-controlled repositories ensured consistent deployment across different machines. This approach minimized the risk of software incompatibilities and provided a reliable foundation for ongoing development.

The redesigned GUI significantly enhanced accessibility, particularly for non-technical users. The graphical interface enables intuitive control of the chamber, while the CLI provides advanced users with powerful scripting capabilities. Feedback from beta testers highlighted the user-friendly design, emphasizing the streamlined setup and real-time monitoring features. Improvements in data acquisition and logging also received praise, with researchers noting the system's ability to provide actionable insights during long-duration experiments.

Future Work

While the project has addressed major challenges, several areas require further development to fully realize the system's potential:

1. Deployment on Hardware: Final testing on the actual deposition chamber hardware is a priority. This phase will involve integrating the software with physical devices and addressing any unforeseen compatibility issues. Ensuring seamless communication between the software and chamber components is critical for operational success.
2. Custom User Interfaces: Developing additional user interfaces tailored to specific research requirements is essential for broader adoption. Mobile-accessible dashboards and specialized visualization tools can further enhance usability, enabling remote monitoring and control.
3. Advanced Data Integration: Incorporating real-time data analysis tools and machine learning algorithms is a key focus for future work. These enhancements would allow researchers to predict optimal sputtering parameters and dynamically adjust experiments based on real-time trends.
4. Multi-Chamber Coordination: Expanding the system's capabilities to manage multiple chambers simultaneously would greatly benefit facilities with diverse experimental needs. This feature would streamline resource allocation and improve overall efficiency.
5. Interoperability with Beamline Systems: Enhancing the system's interoperability with other NSLS-II beamline systems is another important goal. Seamless data exchange between the deposition chamber and beamlines can support cross-platform experiments, enabling more complex and integrated research projects.

Future work will also include refining error-handling mechanisms and improving the responsiveness of the software. Collaborative feedback from researchers and engineers will guide these efforts, ensuring the system evolves to meet the needs of the scientific community.

Impact on Laboratory and National Missions

The modernization of the deposition chamber aligns directly with NSLS-II's mission to advance synchrotron-based research. By providing state-of-the-art tools for thin-film deposition and nanofocusing optics, the project enhances the laboratory's ability to support cutting-edge experiments. Researchers now have access to a more reliable and adaptable system, which translates to improved experimental efficiency and reproducibility.

On a national scale, this project contributes to the Department of Energy's (DOE) goals of fostering innovation in scientific instrumentation and automation. The enhanced control software strengthens NSLS-II's role as a leader in synchrotron science, supporting diverse applications in materials science, medicine, and energy. Additionally, the project's emphasis on open-source frameworks like EPICS and Bluesky reflects a commitment to community-driven development. This approach not only accelerates progress within NSLS-II but also serves as a model for other research facilities looking to modernize their systems.

The system's potential for real-time data analysis and predictive modeling further positions NSLS-II at the forefront of technological innovation. By leveraging advanced computational techniques, the laboratory can provide researchers with deeper insights, driving breakthroughs in their respective fields.

Conclusion

The transition to an EPICS-compatible control system represents a transformative advancement for the Deposition Laboratory at NSLS-II. By integrating modern frameworks such as Ophyd and Bluesky, the project has addressed long-standing limitations, improving the chamber's usability, scalability, and adaptability. These enhancements not only streamline current operations but also prepare the system for future challenges in synchrotron science. The success of this project underscores the importance of modular design, collaborative development, and user-centric interfaces. These principles have guided every phase of the modernization effort, ensuring the system meets the diverse needs of researchers and engineers. As the software undergoes final testing and deployment, its impact on NSLS-II and the broader scientific community is expected to grow, solidifying its role as a cornerstone of advanced materials research.

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