Robotic Operations for Material Processing at Scattering Beamline

Eric Xiao, Department of Mechanical Engineering, Stony Brook University, Stony Brook, NY, 11790
Ruipeng Li, National Synchrotron Light Source II, Brookhaven National Laboratory, Upton, NY, 11973

Abstract

To maximize the usage of valuable photons in synchrotrons, it's critical to introduce automation protocol and promote the safe operation at beamlines. The robot-centered operation not only improves the throughput of the sample transportation, demonstrated at NSLS II [1], but also provides opportunities for more complicated operations, such as in-situ and operando studies. These requires fine tuning of sample and equipment under in-time monitoring. Our approach is to integrate ROS2-based UR robot and python-based bluesky to create an interactive environment for precise operation at the CMS beamline. We initially developed a modular pipettor using RS-485 through the robot's internal cabling to control a microcontroller. We employed closed-loop control was employed for precise volume dispensing and automated tip exchange routines. Second, we integrated optical cameras in ROS 2 that performs guided walkthroughs of beamline stations to generate high-resolution (~2 cm) point-cloud maps. These maps feed into planning stack, enabling the robot arm to execute automated waypoint trajectories in arbitrary layouts. By integrating both modules into the erobs library, we enabled precise liquid-handling routines in parallel with adaptive navigation.

Introduction

Synchrotron beamlines operate in a unique environment where precision, safety, and throughput must coexist. Unlike industrial robotics applications with fixed layouts, beamline environments are constantly reconfigured as different experimental setups are installed, creating dynamic obstacles that traditional pre-programmed robots cannot handle. Simultaneously, the push toward in-situ and operando studies demands liquid handling capabilities that can operate within the tight spatial constraints and radiation environment of active X-ray experiments.
This work makes two key contributions:

1. **Robotic pipettor–** A lightweight, 3-D-printed tool designed for rapid tool-changer swaps. It automatically actuates the pipette, replaces tips, and dispenses volumes as small as 5 µL with repeatability. Custom firmware and ROS 2 nodes tie everything together, delivering a fully plug-and-play liquid-handling workflow.
2. **Vision-based obstacle avoidance module -** A camera-driven system that can quickly scan the workspaces, shows the robot where everything is, and lets it move safely without bumping into equipment. This provides the ability to set up the robot arm at any beamline rapidly.

The pipetting end effector enables real-time sample modification during X-ray exposure, supporting advanced experimental techniques like time-resolved studies of chemical reactions or phase transitions. The vision-based navigation system eliminates the need for extensive teach-pendant programming when beamline layouts change, allowing the same robot to adapt to different experimental configurations within hours rather than days. Together, these modules represent a significant step toward truly autonomous beamline operation, where robots can safely and intelligently respond to the dynamic requirements of cutting-edge materials science research.

Pipettor module

This module consists of two parts, they are:

Hardware:
- Microcontroller server for command processing and actuator control
- Dual linear actuators for pipette dispensing and tip ejection
- Modular, tool-changer compatible design
- Secure pipette holder (0.5% deflection at 20N)
- Integrated LED lighting system for status monitoring and sample illumination

Software
- Bidirectional RS485 communication drivers
- ROS 2 action server integration
- Universal Robot ethernet interface
- Real-time command processing
- 3D model (URDF) for motion planning

Design Requirements
- Compatible with Wingman part changer automatic exchange mechanism

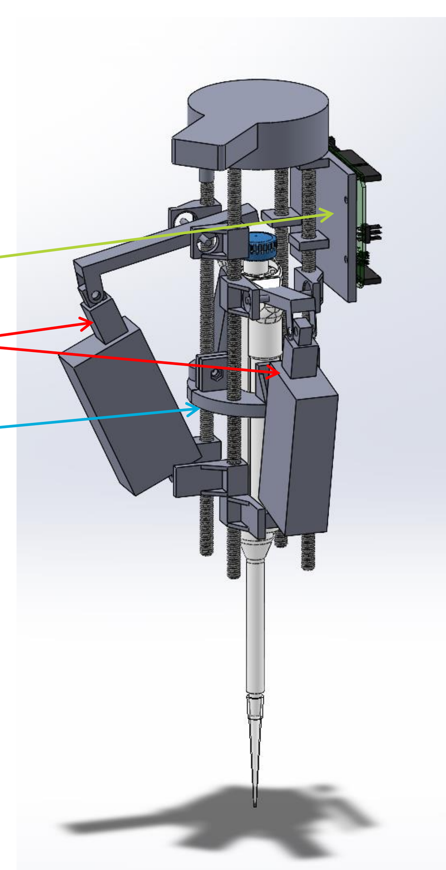

Figure 1: CAD model of the end effector

Figure 2: Prototype deployed on the CMS UR5e

Tool Exchange Sequence

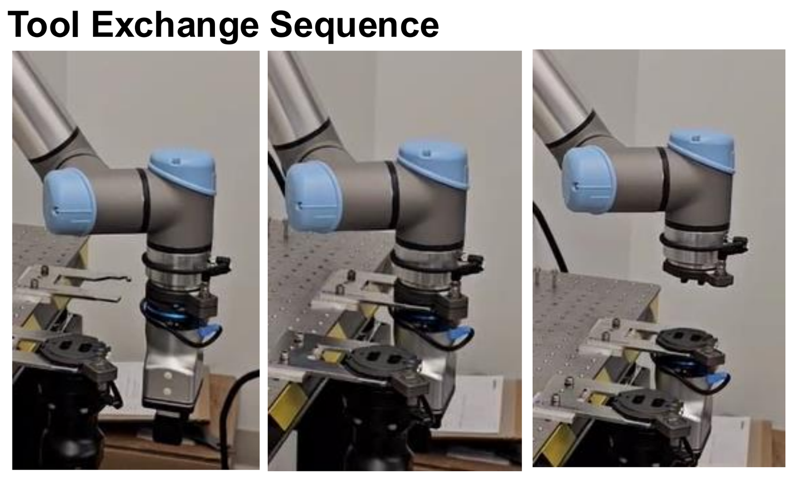

Figure 3: Tool part holder

Vision service module

An optional ROS 2 package enabling real-time environment awareness:

- **3D Workspace Mapping**: ZED 2i stereo camera generates real-time environment mesh
- **ROS 2 Data Publishing**: Makes 3D scan data available to other systems
- **MoveIt Compatible**: Outputs formatted for motion planning integration
- **Calibration Tools**: Hand-eye calibration package for robot localization
- **Documentation**: Setup guides for beamline deployment

Figure 4: Scanned mesh of the CMS Robot

System Overview

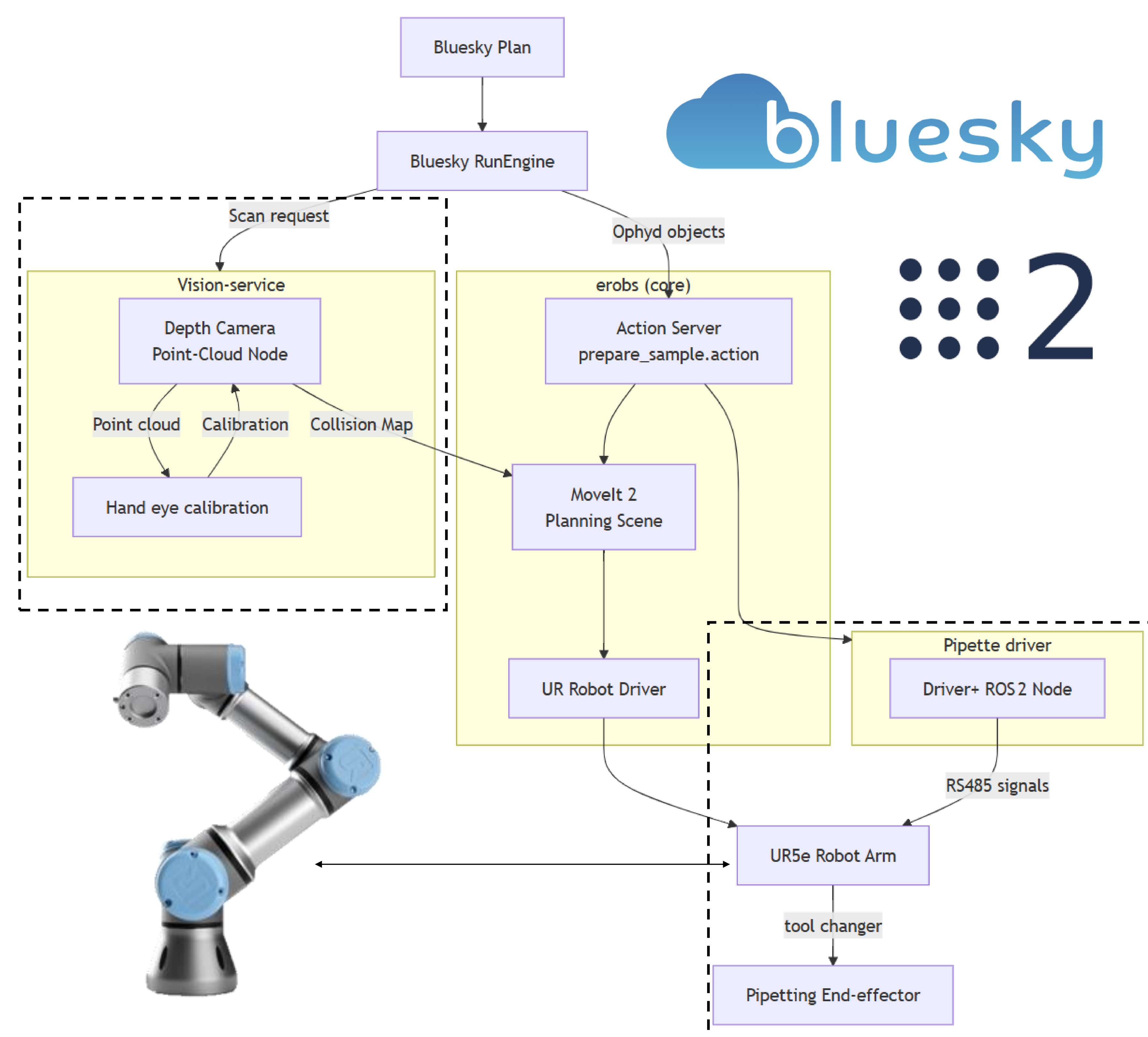

Figure 5: Graph illustration of system architecture

Results and Outlook

Both modules demonstrate successful operation with reliable liquid handling and effective environment scanning capabilities. The modular architecture enables rapid reconfiguration for different experimental setups.

Future Development :
- **Software Virtualization**: Implementing Podman containerization for consistent deployment
- **Tool exchange**: Implementing tool exchange protocols and Bluesky-ROS integration
- **Deployment Standardization**: Developing consistent installation procedures and documentation for deployment at multiple beamline

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Tech Terminology

ROS 2 – Open-source "operating system" that allows robot parts (Nodes) to talk to each other.
Nodes – A ROS 2 concept, each node is a piece of the robot that does something.
Moveit 2 – Open-source planner that finds collision-free paths for the robot arm in real time.
Rviz – 3-D visualizer used to debug perception and planned trajectories in ROS 2.
Bluesky – Python framework the beamlines at NSLS use to orchestrate experiments.
UR5e – A six-jointed, human safe robot arm that is being used in this project. Produced by Universal Robots.
UR Robot Driver – ROS2 driver that streams joint states and accepts commands for the UR5e robot.
Action Server – ROS 2 component that handles long-running tasks with feedback, preemption, and status reporting
URDF – Unified Robot Description Format, XML files that define robot geometry and kinematics for motion planning
RS485 – Industrial communication protocol enabling reliable data transmission over long distances with noise immunity
Hand-eye Calibration – Process of determining the precise transformation between camera and robot coordinate frames
Stereo Vision – Depth perception technique using two cameras to generate 3D point clouds and meshes
Point Cloud – Collection of 3D data points representing surfaces and objects in the robot's environment
Tool Changer – Automated mechanism allowing robots to swap end-effectors without manual intervention
End-effector – The "hand" of the robot – ex. Pipettor, robotic gripper etc
Collision Map – 3D representation of objects used by motion planners to avoid collisions
Joint States – Real-time position, velocity, and effort data from robot actuators

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Reference

[1] C. Fernando, D. Olds, S. I. Campbell and P. M. Maffettone, "Facile Integration of Robots into Experimental Orchestration at Scientific User Facilities," 2024 IEEE International Conference on Robotics and Automation (ICRA), Yokohama, Japan, 2024, pp. 9578-9584, doi: 10.1109/ICRA57147.2024.10611706

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