Closing the Laboratory Automation Education Gap: A White Paper on smartBench for Life Sciences Training

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***Abstract*—Life sciences and natural sciences students currently receive insufficient training in laboratory automation despite growing demand for automation expertise in biomedical research and biotechnology. A primary barrier is limited access to cost-effective, education-suitable laboratory automation equipment. This white paper outlines smartBench as a proposed modular, sterile robotic workstation intended to address this education gap. It builds on open-source principles with standardized interfaces (ROS2, SiLA2, LADS OPC UA) and integrates individually validated building blocks, including a low-particle compliant gripper, a standardized electrical tool-changing flange, and a BSL-2-compatible enclosure design, into a coherent platform vision for teaching laboratory automation across universities, medical schools, and technical institutions. This paper outlines system architecture, safety, and standardization, and invites community input, expertise, and partnerships to realize this platform.**

***Index Terms*—Laboratory automation, robotics in life sciences, educational robotics, sterile robotic workcell, open-source hardware and software, robotics education and training**

I. Introduction

The Laboratory Automation Skills Gap. Laboratory automation is established in industrial manufacturing but lags in biomedical research and education [4]. Life scientists lack hands-on training in robotics, standards (SiLA2, LADS OPC UA), and automation, hindering reproducibility and innovation. **Current barriers** include high investment costs for sterile setups (BSL-2) [10], proprietary systems unsuitable for flexible teaching [4], and institutional silos between technical universities, medical schools, and life sciences departments [13]. Democratizing lab automation requires open-source and open-hardware cultures with affordable, user-driven solutions that lower entry barriers for a wide range of research groups [4].

Beyond isolated workflow digitization. Recent work on structured laboratory digital transformation has shown that Internet-of-Things-based approaches can improve data integrity, sample traceability, standardization, walk-away time, and process efficiency in real R&D settings [5]. Most such approaches are centered on individual workflow steps and do not provide overarching concepts for sterility, product, and operator protection as required in many laboratory environments.

Scalability Challenge Many research laboratories have devised ingenious bespoke automation solutions tailored to their specific needs [4, 9]. However, these systems typically operate reliably only in the environment they were designed for and only when maintained by the original developer, placing them at Technology Readiness Level (TRL) 3–4 [11]. They depend on undocumented tacit knowledge, custom interfaces, and site-specific calibration, preventing adoption by other groups. To truly democratize and scale laboratory automation, the community must advance toward TRL 5–7 systems—validated in relevant environments and robust enough to be deployed, installed, and operated by users other than the original developers. This demands deliberate engineering for portability, modularity, standardized interfaces, and comprehensive documentation—the core design philosophy of smartBench.

smartBench is therefore proposed as an open-source reference platform intended to help close this broader gap. It is designed to be compact, intuitive at human scale, and modular for education, enabling a transition from manual BSL-2 work with an open front and raised robotic arms for standard sterile tasks to future automated operation with a closed front window for fully robotic execution, without disrupting established workflows.

II. Design Principles

To democratize laboratory automation education, future platforms should follow a small set of clear design principles. First, they should be *affordable and reproducible*, so that teaching laboratories can deploy them without the capital requirements of industrial workcells. Second, they should be *modular and transferable*, allowing subsystems, tools, and workflows to be adapted across institutions rather than remaining tied to a single expert-built setup. Third, they should be *open by design*, with documented hardware, software, and interfaces that reduce vendor lock-in and support community-driven extension. Fourth, they should be *safe by architecture*, separating manual teaching and autonomous execution in time and space while preserving operator, product, and process protection. Fifth, they should be *standards-based*, using interoperable interfaces such as ROS2 and SiLA2 to support long-term integration of heterogeneous devices. Finally, they should be *education-first*, enabling progressive transition from manual sterile work to automated workflows without requiring advanced robotics expertise from students or instructors.

III. System Overview

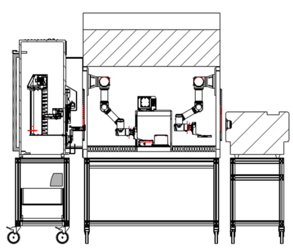

Fig. 1. Concept illustration of smartBench: a modular robotic workbench with a standardized electric flange for quick tool changes and diverse end-effectors such as grippers or printheads, intended to enable flexible tissue engineering automation from biomaterial shaping to sample handling. It combines a BSL-2 enclosure, sterile hoods, low-particle CrocoGrip mechanisms [2], and sterilizable, sealed serial kinematics to target cleanroom compatibility for cell culture labs and medicinal pre-GMP applications

smartBench is conceived as a hardware-software platform for **dual manual and automated use**, built on a standard sterile bench with side ports for peripherals and dual 6-axis robotic arms. The platform is intended to operate in two distinct modes. In **manual mode**, the front would remain open and the robotic arms raised, locked, and drive-disabled, providing an unobstructed BSL-2 workspace for conventional sterile work. Four eye-in-room cameras would passively record operator actions and generate demonstration data for subsequent offline imitation learning without requiring direct interaction with the robotic system [15, 14]. In **automated mode**, the enclosure would be sealed and the robotic arms would execute learned or programmed tasks autonomously, with AI-based anomaly detection intended to support 24/7 walk-away operation. Because human presence and robot motion are strictly separated in time and space [7], this architecture would enable use of standard industrial manipulators without requiring collaboration-certified robots.

This socio-technical design is intended to avoid workflow disruption by allowing existing manual processes to continue alongside scalable automation, with open-source CAD files and software on GitHub, intuitive operation that would require no robotics expertise in manual mode, modular extensions, and integration intended to bridge faculties and support future workforce training. Over time, an increasing share of manual tasks could be transferred to automated execution, enabling a gradual transition toward broader laboratory automation [6].

Existing platforms. Current solutions tend to fall into three categories: low-cost but functionally narrow open platforms, high-performance but proprietary industrial systems, and highly capable academic prototypes that remain difficult to transfer beyond the originating laboratory (TRL¡5). The Opentrons OT-2, for example, has significantly lowered the entry barrier through competitive pricing, open protocol development, and community-driven workflow sharing [12]. However, it does not natively provide the spatial manipulation and peripheral instrument handling required for multi-step laboratory workflows, which typically require additional third-party hardware. To the best of our knowledge, no user-friendly open-source platform at approximately TRL5–7 currently combines sterile enclosure, flexible spatial manipulation, and instrument integration for broader laboratory automation tasks. smartBench is proposed to address this gap.

IV. Safety

The smartBench safety concept is designed to improve operational safety by separating human demonstration from robotic execution. During teaching, the operator would work inside the open bench while four eye-in-room cameras would passively record the task. The robotic arms would remain raised, mechanically secured, and drive-disabled, thereby reducing the risk of human–robot contact. Recorded demonstrations would be processed offline, and the resulting trajectories would be validated within a ROS2-based software stack, including simulation and collision checking prior to execution.

Robotic execution would only be enabled after the BSL-2 enclosure had been closed, sealed, and verified by the relevant sensors [7]. During execution, eye-in-room and eye-in-hand cameras would continuously compare the observed workspace with the expected simulated state. Significant deviations would trigger a protective stop and transition the system into a defined safe state. As the platform is also intended to handle liquids, spill detection would provide an additional safety layer. Hazardous leaks or spills would result in automatic experiment termination, process shutdown, and operator notification to prevent propagation into the wider experimental line. Unexpected contact would be monitored independently through integrated joint-torque sensing or virtual torque estimation [8]. A manual emergency-stop function would provide a final fail-safe measure for unforeseen hazardous behavior.

Overall, this layered safety architecture is intended to enable the use of standard industrial manipulators in educational BSL-2 environments while maintaining operator, product, and process protection.

V. Standardization and Open-Source Hardware

The smartBench is designed to achieve vendor agnosticism through open standards that reduce proprietary dependencies. Its software architecture is intended to rely on open interfaces such as SiLA2 for lab device interoperability and ROS2 for robot control, enabling seamless integration of diverse hardware without vendor-specific drivers. On the hardware side, the standardized flange design with universal power (5/24 V), and serial comms ensures compatibility across robots and the flexibility to match grippers and peripherals from any source to given use cases.

A. Flange for automated tool changing

The automated electrical flange enables tool-free, rapid end-effector changes under ROS2 control, supporting plug-and-play integration of grippers, pipettes, or custom tools without mechanical reconfiguration. This standardization ensures compatibility across the dual 6-axis robot arms while maintaining sterile BSL-2 conditions, reducing swap times from minutes to seconds and enabling seamless workflow transitions between manual and automated modes[1]. The flange CAD files are freely available on GitHub.

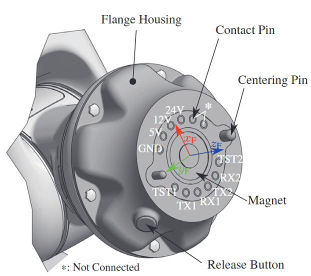

Fig. 2. A custom flange enables quick and automated end-effector mounting/dismounting, supplying 5/24 V power and serial comms via pins. A permanent-electromagnet with centering pins safely secures even in case of power outage and allows zero-force mating while internal cabling and sealed housing preserves sterility.

B. General-Purpose Laboratory Gripper

An example of an end-effector compatible with this standardization concept is CrocoGrip, a compliant-mechanism-based robotic gripper already developed for clean-room laboratory automation and sterile tissue-engineering applications [3]. Within smartBench, it serves as an existing hardware building block that can be integrated through the standardized tool interface described above, so the platform builds on a validated gripper rather than introducing a new one from scratch. Its monolithic structure supports straightforward disassembly, cleaning, autoclaving, and maintenance by non-expert users, while interchangeable jaws enable handling of common laboratory vessels such as microplates, Falcon tubes, and Petri dishes [3].

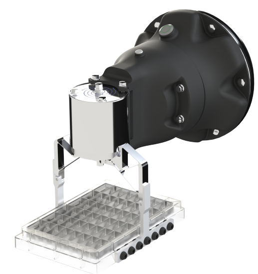

Fig. 3. The CrocoGrip was designed as a general-purpose sterile laboratory gripper for tissue engineering to minimize contamination risks from particles. Its compliant mechanism ensures low particle generation, while maintaining easy cleanability and sterilizability—even for non-experts [2]

C. Visual Servoing, Anomaly Detection, and Collision Control

The smartBench is designed to include four eye-in-room cameras for comprehensive, redundant workspace surveillance and object detection, providing unobstructed monitoring independent of any single viewpoint. A gripper-mounted eye-in-hand camera is intended to support precise visual servoing using stereo vision or neuromorphic sensors for high-speed, low-latency feedback in dynamic settings. Semantic scene descriptions would enable high-level comparisons of expected versus real views from ROS2 simulations, fusing them with on-site processing for robust anomaly detection, collision avoidance, and adaptive control without pixel-level matching.

D. Imitation Learning

The four in-room cameras are intended to enable multi-view recording of human demonstrations, yielding rich visual data for asynchronous imitation learning that supports no-code robot teaching [15, 14]. Unlike synchronous methods requiring direct teleoperation, asynchronous imitation processing would operate on offline video observations without user–robot interaction, improving safety and accessibility in the teaching setting [15, 14]. Consequently, this approach would obviate the need for collaboration-certified robots, broadening applicability to standard industrial manipulators.

E. SiLA Interface for Plug-and-Play Device Integration

A refined SiLA2-ROS2 bridge will be developed to seamlessly integrate the workcell into SiLA-based laboratory automation. SiLA features will incorporate redundant identification through barcode mapping and robust position tracking, eliminating the need for fixed nests.

F. CI/CD Principle for Efficient Collaboration

Our goal is to establish identical workcells for hardware and software developers, teaching facilities, and research labs. By interconnecting them via a shared repository, novel approaches and algorithms can be directly deployed to physical devices, transferring CI/CD principles to the hardware domain for seamless, reproducible experimentation and rapid iteration.

VI. Conclusion

This white paper argues that closing the laboratory automation education gap requires more than isolated teaching tools or bespoke laboratory prototypes. The field needs affordable, safe, modular, and openly documented reference platforms that can be transferred across institutions and disciplines. smartBench is proposed as one such platform blueprint, combining manual sterile work, future robotic execution, and standards-based integration within a single educational architecture. We invite collaboration on implementation, curriculum design, and reproducible deployment to advance laboratory automation training in the life sciences.

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