Scalable Low-Cost Laboratory Automation: A Digital Twin-Integrated Robotic Platform for Autonomous Liquid Handling

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Abstract

Laboratory automation remains limited by the prohibitive cost of commercial liquid handling systems. To address this barrier, we developed a low-cost liquid handling robot by modifying a consumer-grade Cartesian 3D printer, replacing the extruder with a precision single-channel pipette and enabling programmable aspiration and dispensing through direct G-code control of the X–Y–Z gantry. To improve transparency and reproducibility, we implemented a real-time digital twin that synchronizes bidirectionally with the physical platform, mirroring kinematics, pipetting states, and workflow progression.

As a proof of concept, the robot performed sequential exchanges of differently coloured aqueous solutions in a mixing bath, while an integrated **RYB sensor** quantified colorimetric changes during transfers; all motion and sensor data were streamed live to the digital twin for synchronized visualization and logging. The agreement between measured RYB responses and expected mixing behavior validated correct execution and demonstrated real-time experimental tracking. Furthermore, to enhance system self-regulation, we integrated the **CEID™ (Cooperative Explorer for Inverse Design)** framework by leveraging inverse design to minimize the distance to desired targets. CEID™ transforms the workflow from iterative guessing into a goal-driven search, enabling higher degrees of autonomy in experimental optimization. This work establishes a scalable, cost-effective physical–virtual framework for accessible laboratory automation and digital experimentation.

Keywords: Laboratory Automation, Digital Twin, Robotics, 3D Printing, Unity, Autonomous Experimentation, Inverse Design, CEID™.