

Development of a Physical AI-Based Maintenance Manipulator Robot for Steam Generator Tube Plug Installation

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1. Introduction

Steam generator (SG) heat exchange tubes in nuclear power plants degrade over time due to stress corrosion cracking and mechanical wear, requiring periodic plugging of failed tubes to preserve primary coolant integrity. The dense tube-sheet geometry of the SG water chamber—hosting up to several thousand tubes in a high-radiation environment—makes manual tube plug installation labor-intensive and exposes workers to significant occupational radiation, motivating strong demand for remote and automated solutions.

Prior work has demonstrated digital twin (DT) and deep reinforcement learning (DRL)-based robotic automation for confined SG maintenance tasks: Park et al. [1] reported a 92.0% nozzle-dam replacement success rate in a high-fidelity DT with subsequent real-robot validation. Earlier, a radiation-hardened SG tube inspection/maintenance robot integrating eddy-current testing, brushing, and mechanical tube plugging was developed at KAERI [2]. Building on our earlier in-bore EDM work for foreign-object management in SG tubes [3], the present study develops a manipulator platform specifically for tube plug installation. We report component-level integration and preliminary verification results obtained from real-robot mockup tests. This work is conducted as part of the AX (AI transformation) consortium project on physical AI-based nuclear maintenance, supported by the Ministry of SMEs and Startups (MSS), Korea. Physical AI here denotes learned visual perception coupled with a physics-based digital twin and supervisory execution logic; fully autonomous insertion via learned contact control is outside the scope of this paper.

2. Methods and Results

2.1 System Overview

The platform consists of a 6-DOF collaborative manipulator (Dobot CR10) with an end-effector-mounted endoscope camera (eye-in-hand configuration) for visual servoing, paired with a digital twin constructed in NVIDIA Isaac Sim. A YOLOv8-based detector localizes tube-sheet holes, and a cuMotion planner generates candidate collision-free trajectories within the twin; execution of the complete insertion sequence on the physical system remains future work.

The component-level architecture, including the parts not yet integrated, is shown in Fig. 1.

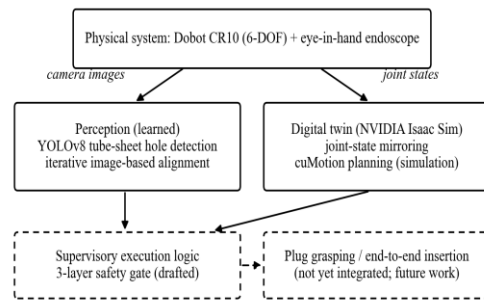


Fig. 1. Component-level system architecture; dashed blocks are designed but not yet physically integrated.

2.2 Vision-Based Tube Localization

Tube-sheet hole detection used a YOLOv8 model [4] fine-tuned with a mixed dataset of synthetic images and images acquired from a physical mockup. A model trained only on synthetic images produced zero detections on real images; incorporating physical-mockup frames in training raised performance to precision $P = 0.97$ and recall $R = 0.94$ on the available physical-mockup evaluation images.

Intrinsic calibration of the endoscope camera yielded an RMS reprojection error of 0.124 px. Hand-eye calibration between the camera and the end-effector was then carried out with four independent methods (TSAI, PARK, HORAUD, DANIILIDIS), which produced mutually consistent camera-to-end-effector translation estimates of $t = [2.1, -46.6, 47.2]$ mm; the PARK solution was adopted. In an iterative image-based alignment test on the physical mockup, the pixel-space alignment error was reduced from 195.6 px to 1.3 px, corresponding to approximately 0.23 mm at the working distance used (Fig. 2), and a separate marker-based alignment trial converged from 29 px to 0 px (within the pixel-grid resolution) in four correction iterations.



Fig. 2. Tube-sheet hole detection overlay from the onboard endoscope camera during the physical-mockup alignment test (measured data).

2.3 Precision Positioning and Mockup Bolt-Insertion Trials

The kinematic performance of the CR10 was characterized in real-robot tests. The measured peak Joint-1 speed and peak TCP speed were 122.04 deg/s and 1,238 mm/s, respectively. A 13-point spline trajectory was executed with a joint tracking error of 0.0062 deg.

An encoder-feedback repeat-positioning test over 30 A-B-A round trips at one pose pair, applying the ISO 9283 RP formula (not the full ISO 9283 procedure), yielded $RP = 0.038$ mm; external optical metrology was not employed, so this value reflects encoder-based repeatability only. In a mockup bolt-insertion trial, the controller reported the difference between the commanded and reached positions as 0.00 mm, indicating only that the commanded target was reached within the controller's own resolution (<0.01 mm); no independent physical measurement of the tip position error was obtained (Fig. 3).



Fig. 3. Real-robot mockup test: (a) manipulator performing camera-based verification beneath the mockup tube sheet; (b) mockup bolt inserted into a tube-sheet hole.

2.4 Digital Twin and Path Planning

A real-to-simulation twin link was established by streaming joint states from the CR10 controller to Isaac Sim; pose correspondence was confirmed across four representative configurations. Collision-free path planning within the twin used cuMotion, with a reported endpoint deviation of 0.18 mm (simulation); this is a simulation-only planning result, not an end-to-end insertion result. A three-layer supervisory safety-gate concept—covering kinematic and collision feasibility, prediction–observation force consistency, and out-of-distribution detection—has been drafted; its detailed criteria, thresholds, and closed-loop validation

remain as future work. Table I lists the tube-sheet hole detection performance and its measurement scope.

Table I: Tube-sheet hole detection performance

Item	Result	Scope / condition
Tube-sheet hole detection	$P = 0.97$ / $R = 0.94$	mixed-data fine-tuning; mockup evaluation images

3. Conclusions

We have presented a manipulator platform under development for SG tube plug installation and reported component-level results from physical-mockup tests together with separately identified simulation-only results. These results do not establish externally measured positioning accuracy or end-to-end plug insertion.

At this stage, end-to-end closed-loop tube plug insertion using real plug hardware has not yet been demonstrated, and the stereo-vision configuration for in-chamber depth estimation and the plug-grasping sequence have not yet been physically assembled and integrated. Internal integration is planned through September 2026, followed by an October mockup demonstration of alignment, insertion, and removal of a temporary plug model. Of these, alignment and insertion precede plug expansion in the installation process, while removal supports repeated mockup trials; the expansion process will be addressed as future work in connection with the demonstration results.

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REFERENCES

- [1] S.-Y. Park, C. Lee, S. Jeong, J. Lee, D. Kim, Y. Jang, W. Seol, H. Kim, and S.-H. Ahn, Digital Twin and Deep Reinforcement Learning-Driven Robotic Automation System for Confined Workspaces: A Nozzle Dam Replacement Case Study in Nuclear Power Plants, *International Journal of Precision Engineering and Manufacturing-Green Technology*, Vol. 11, pp. 939-962, 2024.
- [2] H. Shin, S. Kim, Y.-C. Seo, K.-M. Jung, S.-H. Jung, and C.-H. Choi, Development of a Nuclear Steam Generator Tube Inspection/maintenance Robot, *International Conference on Control, Automation and Systems (ICCAS)*, Gyeongju, Korea, October 22-25, 2003.
- [3] S. Nam, B. Kim, and G. Park, A Novel Approach to Foreign Object Management in SG Tubes: The In-Bore EDM System, *Transactions of the Korean Nuclear Society Autumn Meeting*, Gyeongju, Korea, October 26-27, 2023.
- [4] G. Jocher, A. Chaurasia, and J. Qiu, Ultralytics YOLOv8, 2023. <https://github.com/ultralytics/ultralytics>