Automation of Nuclear Power Plant Liquid-Filter Replacement Using FilterBot: Development and Field Demonstration

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1. Introduction

Primary-coolant liquid filters are periodically replaced during normal operation and planned outages to remove foreign material from nuclear power plant systems. The work is performed in narrow, poorly illuminated cavities with high radiation fields. Conventional replacement requires workers to manipulate long extension rods from above the cavity or to enter the work area for alignment and recovery tasks. These indirect actions make it difficult to apply the specified bolt torque uniformly and to verify O-ring seating. Over-tightening, under-tightening, and uneven tightening can therefore degrade the pressure boundary as well as increase occupational exposure.

Human performance measures can reduce errors, but they cannot remove the physiological and cognitive limitations that arise under time pressure, restricted visibility, protective clothing, and radiation-related stress [1]. The SPAR-H framework likewise treats time pressure, complexity, and adverse working conditions as performance-shaping factors that increase human error probability [2]. Replacing the worker's direct physical intervention with a repeatable robotic process is therefore a structural risk-control measure rather than only a productivity improvement.

This study developed and field-demonstrated FilterBot, a five-degree-of-freedom (5-DOF) remote maintenance system for automated liquid-filter replacement. The study focused on field applicability and maintenance-quality improvement rather than a complete derivation of robot kinematics. The system integrates stereo vision, a six-axis force/torque sensor, position-based impedance control, interchangeable tools, and remote monitoring. FilterBot was developed in compliance with the maintenance instructions applicable to the target equipment. To enable its use in actual equipment maintenance, the relevant maintenance instructions were revised to incorporate robot-assisted maintenance procedures. System performance was evaluated through mock-up tests, accredited repeatability testing, torque comparisons with a human operator, and demonstrations at Hanbit Unit 1 and Kori Unit 1.

2. Methods and Results

2.1 Task constraints and mechanical architecture

The target filter housings are installed 1.70–2.15 m below the access level. The available workspace is approximately 1.2 m wide and 2.5 m deep, while the most demanding sealing-water injection filter requires a tightening torque of 275 ft·lbf. A conventional articulated industrial robot could not simultaneously satisfy the reach, collision-avoidance, payload, and high-torque requirements.

FilterBot was consequently designed as a compact 5-DOF dedicated mechanism. The integrated system is 700 mm wide and 1,590 mm high. Its fifth axis provides continuous rotation for bolt operations and delivers a rated torque of 280 ft·lbf and a maximum torque of 364 ft·lbf. The mechanism supports 15 kg in the retracted posture and 30 kg in the extended posture. A mobile base, outriggers, controller, and tool storage are integrated into one platform. Socket-type and hook-type end effectors enable bolt removal, housing opening, filter extraction, insertion, and final closure.

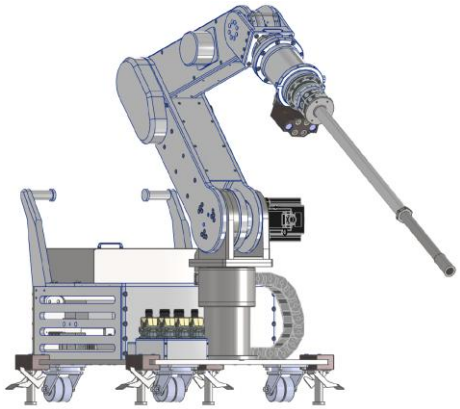


Fig. 1. Integrated mobile-base configuration of FilterBot.

2.2 Vision and force-control strategy

A stereo-camera system locates the housing bolts in three dimensions. After image rectification, edge candidates are obtained with Canny detection and bolt-head contours are identified by constrained ellipse fitting. Matched centers in the left and right images are triangulated using the calibrated focal length and camera baseline [3]. The resulting target coordinates guide the end effector into the vicinity of each bolt.

Physical contact is managed using a six-axis force/torque sensor and position-based impedance control. The

controller modifies the commanded position according to the measured force error so that the end effector behaves as a virtual spring-damper system [4]. Low axial stiffness allows compliant socket insertion, while higher lateral stiffness preserves the rotation center. During removal, the tool follows the bolt lead and stops when abnormal load reaches 90% of the defined limit. During assembly, return load is maintained below 30 N, and the final torque is applied through programmed staged tightening at 80% and 100%. "This sequence helps reduce the risk of jamming, cross-threading, and disruption of the prescribed tightening order.

2.3 Repeatability and torque accuracy

A 2.5 m high dark mock-up reproduced the geometry and illumination conditions of the filter room. Pose repeatability was measured under 100% rated load with a Leica AT960-MR laser tracker according to ISO 9283 [5]. Thirty repeated measurements yielded a maximum repeatability error of ±0.101 mm, approximately one-tenth of the ±1.0 mm design target.

Bolt-tightening performance was compared at target torques of 100 and 250 Nm using a manual torque wrench and FilterBot. At 250 Nm, FilterBot achieved a mean tightening torque of 250.125 Nm with a standard deviation of 0.092 Nm. The human operator achieved 251.7 Nm with a standard deviation of 1.476 Nm. Thus, robotic tightening reduced torque dispersion to approximately one-sixteenth of the manual result while remaining closer to the target value.

Table I: Performance verification results

Metric	FilterBot	Benchmark
Pose repeatability	±0.101 mm	±1.0 mm target
Mean torque (250 Nm)	250.1 Nm	251.7 Nm manual
Torque standard deviation	0.092 Nm	1.476 Nm manual
Maximum axis-5 torque	493.5 Nm	372.9 Nm required

2.4 Nuclear power plant demonstrations

The first field demonstration at Hanbit Unit 1 covered the spent-fuel-pool purification filter and the reactor-coolant-pump sealing-water injection filter. The trial confirmed that laboratory vision parameters required adjustment for oxidized, contaminated, and worn housing surfaces. It also led to practical improvements including lifting eye bolts, modified wheels for floor obstacles, a one-touch tool changer, an integrated socket, and a simplified touch-screen interface.

The improved system was then demonstrated at Kori Unit 1 under conditions outage maintenance operation. The complete sequence—initial positioning, bolt loosening, housing opening, filter exchange, closure, and 100% final tightening—was completed in 1,749 s for the six-bolt reactor coolant filter and 860 s for the three-bolt sealing-water injection filter. These cycle times were comparable to manual work, but the operator remained at a low-dose remote-control location.

2.5 Radiation-exposure reduction

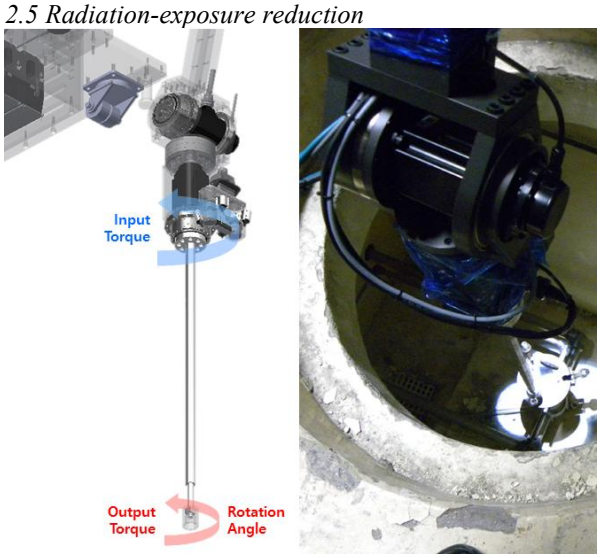


Fig. 2. Fifth-axis torque-transmission structure and field demonstration.

Manual work requires access to radiation fields reported at up to 6.6 mSv/h for the Hanbit Unit 1 task, whereas the remote operating position averaged 1.94 μSv/h. Field data from Kori Unit 1 indicated exposure reductions to approximately 1/25 of the manual level for the reactor coolant filter and 1/75 for the sealing-water injection filter. Under the study's screening assumptions—one annual outage for each of 24 domestic pressurized-water reactors—the two tasks could reduce collective dose by an estimated 89.8 man·mSv per year. This estimate excludes equipment installation, decontamination, and waste-handling activities and should therefore be confirmed by a full-process dose assessment.

Table II: Kori Unit 1 field-demonstration results

Target filter	Cycle time	Exposure reduction
Reactor coolant (6 bolts)	1,749 s (≈29 min)	To ≈1/25
Sealing-water injection (3 bolts)	860 s (≈14 min)	To ≈1/75

3. Conclusions

A compact 5-DOF robotic system was developed to automate high-torque liquid-filter replacement in confined, high-radiation areas of nuclear power plants. Stereo vision and force/torque-based impedance control enabled positioning, bolt manipulation, housing handling, and filter exchange. Testing demonstrated ±0.101 mm pose repeatability, a 250.125 Nm mean torque with only 0.092 Nm standard deviation, complete field cycles of approximately 14–29 min, and exposure reductions of approximately 25- to 75-fold relative to manual work. FilterBot therefore provides a practical pathway from non-contact robotic inspection toward contact-intensive nuclear maintenance. The system was developed in accordance with the maintenance instructions for the target equipment, and those instructions were revised to

incorporate actual robot-assisted equipment maintenance. This provides a procedural basis for field application. Wider deployment will require plant-specific qualification, adaptive perception, full-process dose assessment, and continued integration with nuclear quality-assurance and outage-management systems.

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