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Research on 3D point cloud-based robot arm task automation for accident response at operating nuclear power plants

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1. Introduction

Accident response in operating nuclear power plants presents high demands for both safety and speed, as human access is heavily restricted due to radiation hazards. Robotic automation of crucial tasks—particularly door opening and valve manipulation—can significantly reduce human exposure. Traditional teleoperation approaches, however, require continuous expert oversight and can be inefficient under emergency conditions. To address this, our study proposes a framework that leverages pre-planned robot arm motions in a 3D simulation environment, alongside real-time 3D point cloud recognition, to achieve automated task execution in the field.

Three-dimensional point clouds provide rich geometric information critical for accurate object localization, even in degraded or complex environments. Previous research has demonstrated the potential of perception-driven manipulation using 3D data. For example, Rusu et al. [1] introduced a laser-based perception pipeline that detects doors and handles by segmenting and analyzing the intensity of 3D scans, mounted on a PR2 mobile manipulator, thereby enabling robots to generate door-opening trajectories directly from geometric observations. Müller et al. [2] advanced this field by developing methods for door localization using laser scans, combining neural networks such as PointNet with heuristic approaches to extract keypoints including hinges and handles, which can be transformed into grasp poses for robotic manipulation. In parallel, studies on valve operation have also shown significant progress. Team NimbRo [3] demonstrated an autonomous system for valve stem turning with a wrench tool, in which both the valve stem and the tool were detected in 3D laser scans, and parametrized motion primitives were adapted online to complete the manipulation task successfully.

Despite these promising developments, the integration of simulation-planned motions with real-world perception remains underexplored, particularly in the context of automation for high-stakes environments such as nuclear facilities. The key idea of our work is to bridge this gap by transforming robot arm motions, which are carefully designed and verified in a 3D simulation environment, into executable trajectories that align with the poses of real-world targets identified through point cloud recognition. This approach allows the robot to perform complex tasks such as opening doors and turning valves autonomously, with minimal human input. By tightly coupling simulation-based planning with real-time 3D perception, the proposed framework enhances the accuracy and robustness of robotic task automation and offers a reliable solution for nuclear power plant accident response.

2. Methods and Results

This section describes the configuration of a robot arm equipped with a 3D scanner and the results of experiments involving door opening and valve closing tasks. Technical details of creating a kinematic chain

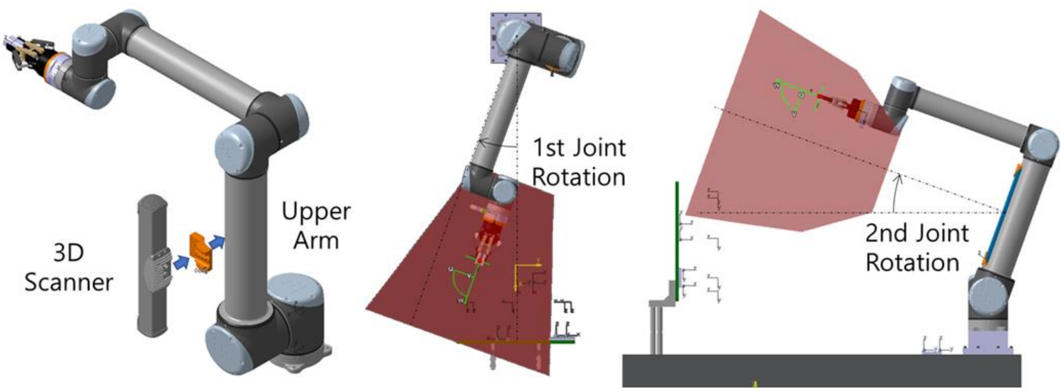

Fig. 1. Robot arm equipped with 3D scanner on its upper arm

and applying pre-planned motions to actual targets are explained in a previous paper [4], so this paper presents the newly modified configuration of the 3D scanner and results of newly conducted experiments.

2.1 Configuration of the 3D scanner

This paper proposes a configuration for attaching a 3D scanner to the upper arm of a robot arm as shown in Fig. 1. This is to expand the scanning volume and maintain continuous relationship between the coordinates of the robot arm and the 3D scanner. In previous studies and industrial applications, 3D scanners have been installed in independent locations or on the end effectors of robotic arms. When the 3D scanner is in an independent location from the robotic arm, the relationship between the coordinate systems of the robotic arm and the 3D scanner changes when the position of the robotic arm changes. When the 3D scanner is on the end effector of the robotic arm, there is a high possibility of interference between the 3D scanner and the robotic arm or target.

2.2 Door opening experiment

The door opening experiment was successfully conducted on a fire door similar to the doors installed in nuclear power plants, as shown in Fig. 2.

The robotic arm is mounted on a small table, similar to how it would be mounted on a mobile platform. In the first step, a 3D scanner mounted on the upper arm of the robotic arm scans the fire door. When the remote operator selects the area near the door handle in the 3D point cloud, the process of finding the exact location of the door handle and transforming the pre-planned motion to the measured location is performed automatically.

In figure 2, steps 2 through 4, which involve the robot arm grasping the door handle, turning it, and opening the door, are performed automatically.

2.3 Valve closing experiment

The valve closing experiment was also successfully performed, as shown in Fig. 3. The valve is located on the opposite side of the door, and the table equipped with the robot remains in the same position when conducting the door opening experiment. Since the 3D scanner is mounted on the upper arm of the robot arm, the 3D scanner can scan the valve when the first axis of the robot arm rotates 180 degrees and the second axis rotates slightly downward. Closing the valve is done in the same way as opening the door.

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3. Conclusions

This study introduced a 3D point cloud–based framework for robot arm task automation in nuclear accident response. By transforming motions planned in a simulation environment into real-world execution through point cloud recognition, the system successfully performed door-opening and valve-closing experiments. A distinctive feature of the approach was mounting the 3D scanner on the robot's upper arm, which expanded the scanning volume and maintained a stable sensor–robot coordinate relationship. The results demonstrate the feasibility of the proposed method for improving automation, accuracy, and reliability in hazardous environments.

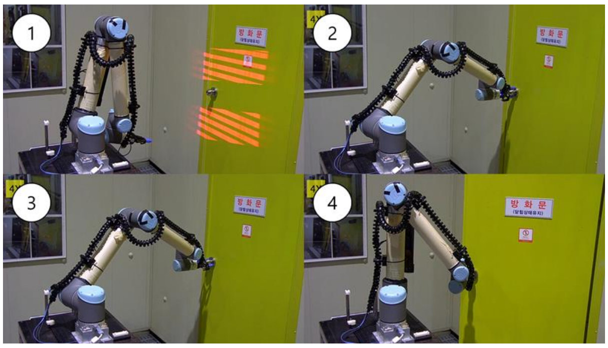

Fig. 2. Door opening experiment.

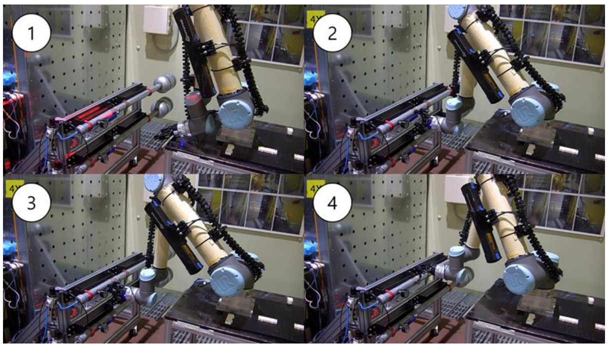

Fig. 3. Valve closing experiment.

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