

Development of a Teleoperation-Based Robotic Testbed to Enable Smart Operations on Legacy Electrical Distribution Panels

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Abstract—This paper proposes the development of a teleoperation-based robotic testbed for smart operation of electrical distribution panel maintenance. Most electrical distribution panels in facilities such as power plants and buildings lack internet connectivity or IoT sensors, requiring on-site human access for operation. To address this limitation, this paper proposes a teleoperation-based intelligent robotic system that enables legacy distribution panels to be operated as if they were smart grid panels. The proposed system incorporates an environment for collecting multimodal data (consisting of RGB sensor data from a mobile dual-arm robot and joint data of the robot arms required for panel operation), which can be used to train robotic Vision-Language-Action (VLA) models. The developed distribution panel testbed can facilitate the transition of existing panels into smart grid-compatible infrastructure without the need for replacement.

Keywords—Smart Grid, Electrical distribution panel, Robotic automation, Robot teleoperation, Maintenance automation

I. INTRODUCTION

Many power systems today utilize IoT sensors and controllers to enable automatic control and remote monitoring functions. In such smart grid-based environments, electrical distribution panels scattered across various locations are connected via IoT sensors and networks, allowing for centralized monitoring and control. However, in facilities such as power plants and commercial buildings, the majority of distribution panels remain offline and do not utilize IoT technology. As a result, tasks such as switch operation, circuit breaker reset, and voltage and current measurement require workers to visit the site in person, which incurs various costs. Additionally, due to the nature of electricity, electrical hazards may occur.

Replacing existing offline distribution panels or legacy distribution panels with internet-enabled smart grid distribution panels or adding IoT sensors requires significant economic costs and time. This paper proposes the introduction of a testbed that utilizes mobile robots to enable remote automatic control of existing electrical distribution panels, similar to those found in smart grid electrical distribution systems, to address these shortcomings. The proposed testbed provides an environment for acquiring multimodal data, including RGB video data obtained by a mobile dual-arm robot and joint angle data of the robot arm required for electrical distribution panel operation, enabling future learning of robot artificial intelligence.

To develop robot AI for distribution panel operations, tasks related to distribution panel operations can be performed through remote control of the robot, and LfD (Learning from Demonstration) [1] or VLA (Vision-Language-Action) [2]

models can be utilized to enable the robot to perform similar tasks in the future by utilizing vision information and joint angle values of the robot mobile base and robot arms during task execution. The robot testbed constructed using the above methods suggests a way to improve existing electrical infrastructure into a smart grid-compatible system without physical replacement, thereby reducing the gap between existing infrastructure and smart grid systems, and contributing to the construction of an automated and safe electrical system.

II. ELECTRICAL DISTRIBUTION PANEL TESTBED

In this study, we constructed a mock distribution panel environment with the same specifications as an actual electrical distribution panel. This simulated distribution panel includes basic elements such as a main circuit breaker, individual circuit breakers for each electrical line, and electrical wiring, enabling various operational tasks to be performed. The distribution panel was designed to utilize low-voltage batteries for safety in experiments and was configured so that there would be no problems even if a robot came into contact with it.

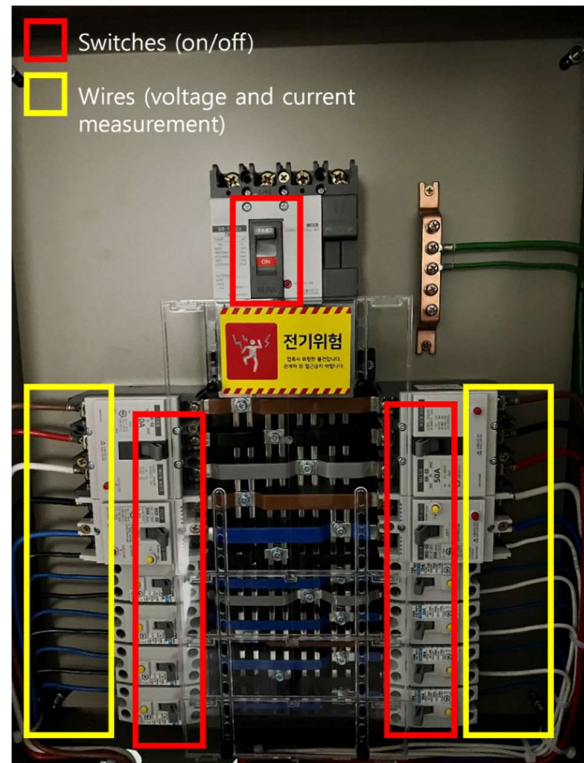


Fig. 1. Electrical distribution panel and target tasks

Figure 1 shows the constructed electrical distribution panel and the target operations performed on it. The switches inside the red box are controlled by the robot gripper, and the wires inside the yellow box can be used for voltage/current measurement. Each wire is connected to the rear for voltage measurement, and the robot can measure data by placing the voltage measuring tip on the desired cable.

III. ROBOTIC TELEOPERATION FRAMEWORK

The robot used to collect the dataset in this testbed is a remote-controlled robot with two arms in a master-slave [3] structure, modeled after Mobile ALOHA [4]. As shown in Fig. 2 below, the robot consists of two master arms located in the blue box and two slave arms in the green box that follow the movements of the master arms in real time. An RGB camera is attached to the top of each Slave arm's gripper and the robot's center, enabling video recording during operation.

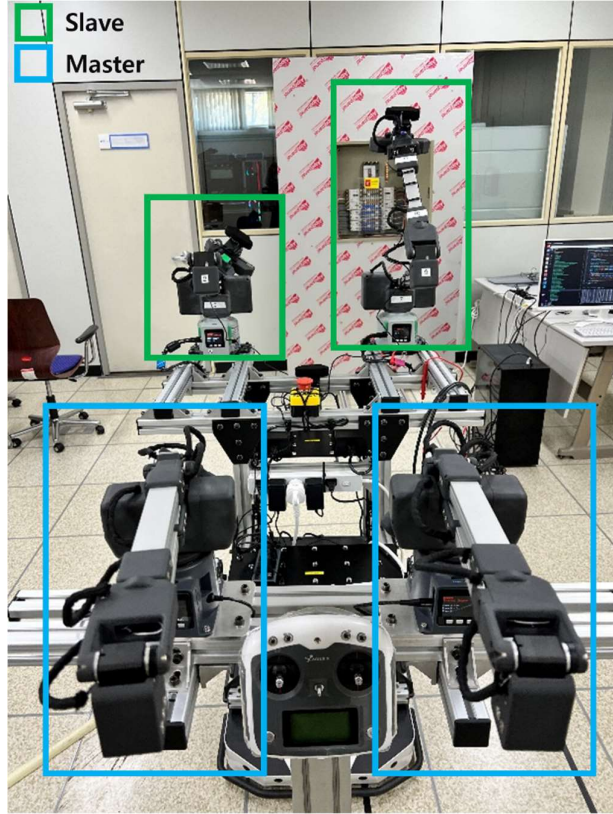


Fig. 2. Mobile dual-arm robot with master-slave structure

To record electrical distribution panel operations, the operator holds the two Master arms located at the rear of the robot and controls them in real time, while the Slave arms at the front perform the same movements and record the motion information. This allows users to perform switch control, voltage measurement, and other electrical distribution panel operations remotely while simultaneously collecting multimodal data. Figure 3 illustrates the teleoperation framework with the distribution panel testbed.

During the collection process, multi-sensor information generated during robot-based operations is stored in a synchronized format with timestamps. The recorded data includes the joint angles of each robot arm, RGB images, and the movements of the mobile base. The resulting robot episode data is composed of a combination of visual and motion

information and can be used for future robot AI learning. In particular, this data can be applied to the latest robot model learning, such as Learning-from-Demonstration (LfD) or Vision-Language-Action (VLA) model, contributing to the implementation of a smart grid-connected electrical distribution panel system.



Fig. 3. Teleoperation framework with distribution panel testbed

IV. ROBOTIC DATASET FOR AI

The teleoperation-based energy facility operation robot testbed proposed in this study will collect data sets for the electrical distribution panel's switch control and voltage measurement tasks in the future. These two tasks are representative basic operations performed in actual electrical distribution panel's operations and are suitable for verifying the possibility of replacing them with mobile dual-arm robots. The robot operation dataset to be collected will consist of three videos, each approximately 15–20 seconds long, recorded at 50 fps and 640×480 resolution. The composition of the dataset to be collected is summarized in Table I. The robot data includes the joint angles of both arms, gripper status values, and the speed and angular velocity information of the mobile base, which are stored in a time-synchronized form with the vision information. As shown in Fig. 4, the vision data is acquired through cameras located on top of both grippers and a camera mounted on the central part of the robot, recording the process of the robot performing switch control and voltage measurement. This data is stored in precise time synchronization with the robot's motion information, resulting in a multimodal dataset that combines visual and motion information. Next, Fig. 5 shows the process of a robot performing switch control and voltage measurement tasks on an actual electrical distribution panel based on the teleoperation of robot arms.

TABLE I. INFORMATION OF THE DATASET TO BE COLLECTED

Item	Description
Task types	Switch control and voltage measurement
Episode duration	15 ~ 20 seconds per episode, at 50 fps
Robot arm data	Joint angles and gripper states of dual-arm
Mobile base data	Velocity and angular velocity
Vision data	RGB images * 3, 640 x 480 resolution



Fig. 4. Example of RGB data acquired during teleoperation

The collected dataset can be utilized for demonstration learning models like ACT [5], and the development of such models can contribute to converting existing legacy distribution panel into smart grid-compatible energy infrastructure.

The robot dataset collected through the testbed constructed in this study can be used for learning imitation learning models for the two proposed electrical distribution panel tasks, and additional task data required by users can be acquired and applied to learning.

Future research will include the following directions. First, we plan to expand the dataset to include new tasks such as cable separation and connection, and removal of protective covers, in addition to switch control and voltage measurement. Second, we plan to train robot AI models to perform these tasks under various conditions using LfD techniques and implement natural language-based task instruction functions by linking them with large language models [6].

Therefore, this study presents physical AI-based technology that enables smart grid-level electrical distribution panel operation by applying intelligent robots to existing electrical infrastructure, and is expected to contribute to future research on energy facility management automation.

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V. CONCLUSION

In this paper, we propose a teleoperated energy facility operation robot testbed for the development of robot artificial intelligence technology that can be applied to existing offline electrical distribution panels in a smart grid environment. The proposed testbed utilizes a mobile dual-arm robot to perform basic electrical distribution panel inspection tasks remotely, thereby providing an environment for collecting multimodal robot datasets.