Development of a Robotic Control System for a Nuclear Disaster Response Robot

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1. Introduction

Nuclear power plants contain large amounts of toxic substances and radiation, making it difficult for humans to perform certain tasks directly. As a result, robotic technologies capable of operating in hazardous environments have been actively studied, with various research efforts exploring their potential deployment in nuclear facilities.

In particular, master-slave robots can accurately replicate an operator's commands, allowing complex tasks to be performed in environments that are difficult for humans to access. However, existing master robots have several limitations.

Specifically, current master robots operate the slave system using sensors attached to each joint without any force compensation mechanism. Consequently, when manipulating the master robot for extended periods, the user must bear the full weight of the robotic arm, leading to operator fatigue. Additionally, the lack of feedback on the slave robot’s status makes precise control challenging during operation.

This paper proposes a novel master robot design and system architecture to address these limitations.

2. Master Robot Mechanism Design

2.1 Master Arm Kinematic Design

Existing master robots consist of actuating pins for each joint and sensors that measure joint rotation. However, as previously mentioned, these robots have several operational limitations.

To address these issues, a motorized joint system was adopted. By equipping each joint with a motor, the system can receive feedback on the slave robot’s current joint angles and overall status, enabling more precise control.

The master robot (Fig. 2) was designed to replicate the joint structure of the slave robot (Fig. 1) exactly. Additionally, to ensure precise control of the slave robot and optimize motion for various work environments, the master-slave scaling ratio was set to 3:1 (Table 1).

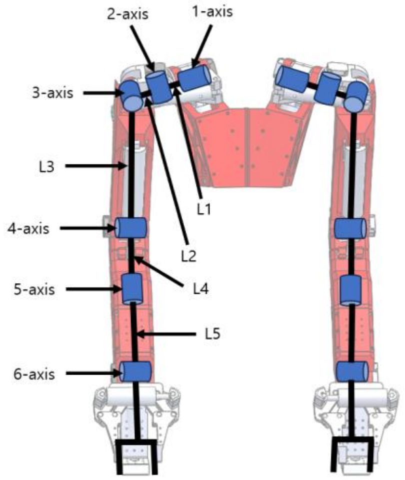

Fig. 1. Structure of the slave robot

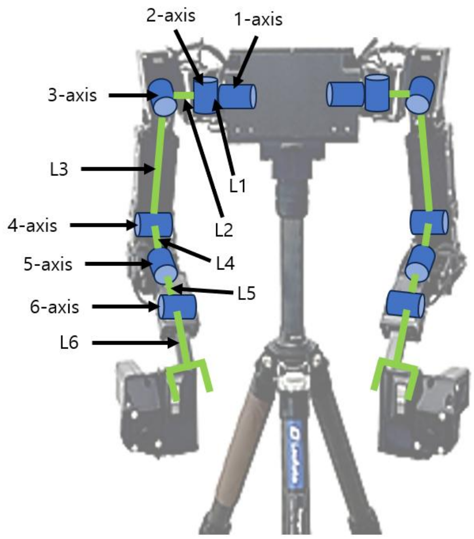

Fig. 2. Structure of the master robot

Table I: Mechanical properties of master-slave robot

	Slave Robot	Master Robot
L1 (mm)	85.5	26
L2 (mm)	72	55.5
L3 (mm)	450	166.75
L4 (mm)	184	75.8
L5 (mm)	266	40
L6 (mm)	245	132
Total (mm)	1302.5	496.05

2.2 Agile Wheel-Mode Gripper

The grippers of conventional master robots are typically designed using either a joystick mechanism or the same structure as the slave robot, making them easy to operate but lacking flexibility. This paper proposes a novel wheel-mode gripper structure to enhance adaptability.

The proposed Agile Wheel-Mode Gripper, shown in Fig. 3, consists of two joints capable of single-axis rotational movement. This design allows precise control of the slave robot's 7th and 8th axes by rotating the wheels. Additionally, as shown in Fig. 4, the mode shift switch enables the robot to switch between different operation modes, such as controlling the throttle and steering of a mobile robot. This provides enhanced mode transition flexibility and control versatility.

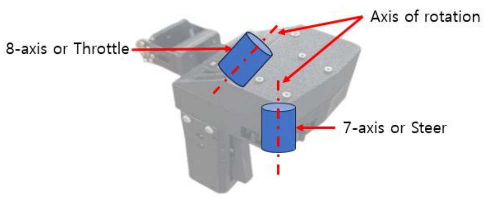

Fig. 3. Wheel-Mode Gripper structure

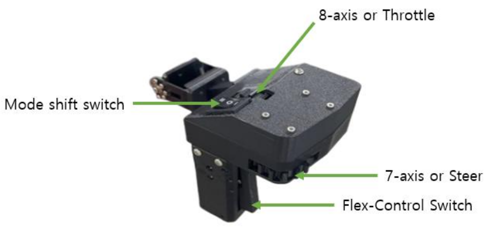

Fig. 4. Schematic configuration of a 2-DOF Wheel-Mode Gripper

3. System Configuration

3.1 Master Robot System Configuration

The overall system configuration of the master robot is illustrated in Fig. 5. In this study, Dynamixel motors are used, and data preprocessing is performed through serial communication between the motors and a Raspberry Pi.

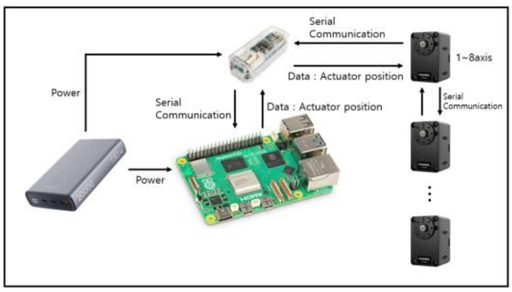

Fig. 5. Master robot system structure

3.2 Master-Slave Data Exchange Process

The Master-Slave robot system is controlled remotely via Wi-Fi. As shown in Fig. 6, each robot communicates wirelessly through TCP/IP to transmit the Master robot's desired state to the Slave robot and the Slave robot's joint states back to the Master robot. When the operator manipulates the Master robot, the information is transmitted to the Slave robot, causing its joints to move, as shown in Fig. 7.

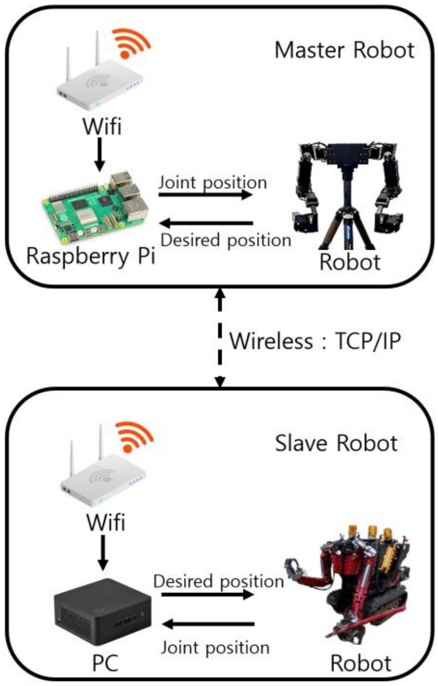

Fig. 6. Master-Slave robot data communication

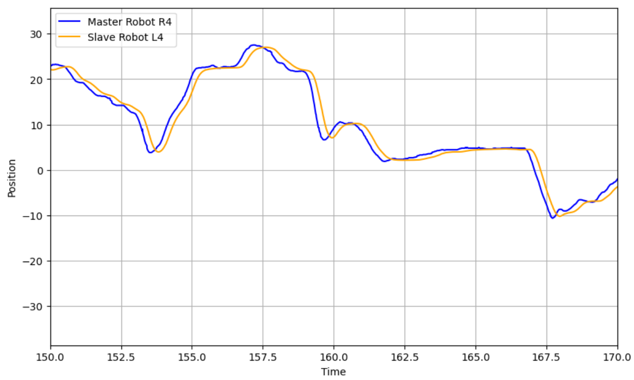

Fig. 7. Position tracking result of Slave robot

3.3 Master Robot Control

The Slave robot, as shown in Fig. 8, consists of each axis driven by a 4-bar mechanism. While the actual actuation is performed by pistons, the position sensing is done through rotating joints. Unlike rotational motors, pistons have a limited operating range, so each joint of the Slave robot has a defined limit angle. The position of each joint in the Slave robot corresponds to the position of the corresponding joint in the Master robot. However, during operation, the Master robot does not receive feedback when the Slave robot exceeds its limit angles, making it difficult for the operator to accurately determine the Slave robot's state.

To address this, a control algorithm was developed using Python to provide feedback on the limit angles from the Slave robot to the Master robot. Additionally, the control of the gripper and mobile robot was also integrated.

As shown in Fig. 9, the Master robot receives the operator's input before operation. The state of the Mode Shift Switch is then determined, and depending on the selected mode, the system controls either the Slave robot or the Mobile robot. In Mode 1, both the Slave robot and the gripper can be controlled. If the desired position sent to the Slave robot exceeds the limit angles, the motors of each joint apply torque to prevent further exceeding, thereby controlling the motion and ensuring safety.

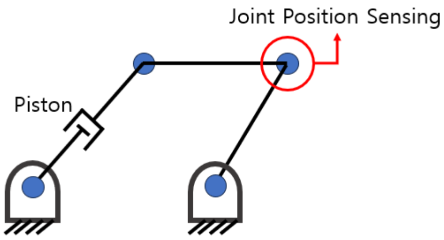

Fig. 8. four-bar structure

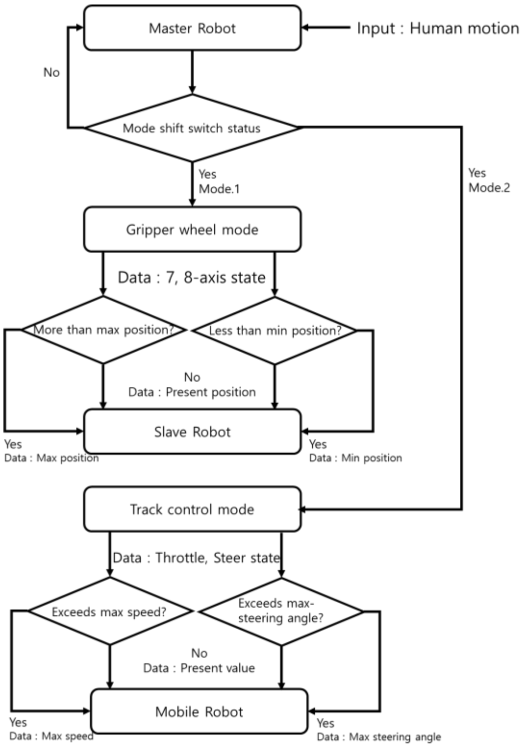

Fig. 9. Master Robot Control Process

4. Conclusions

In this study, a motor-based master robot design, differentiated from existing systems, was proposed, and its performance in controlling both the slave robot and mobile robot was analyzed. Specifically, a limit angle feedback function, which was not available in conventional master robots, was implemented, enabling more precise control. Additionally, the proposed Agile Wheel-Mode Gripper demonstrated the ability to precisely control the gripper of the Slave robot and the Mobile robot.

However, the function of providing feedback on the forces applied to each joint of the Slave robot when lifting an object was not achieved in this study. Future research will focus on adding the capability to provide force feedback to the Master robot, allowing for more intuitive control.

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