Tele-robotic Application for Nozzle Dam Maintenance Operation in Nuclear Power Plants

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Abstract: This paper describes the development of a robotic maintenance system for use in a maintenance operation of the nozzle dam in a water chamber of a steam generator at the Kori nuclear power plant in Korea. The robotic maintenance system was designed to minimize the personnel exposure to a hazardous radioactive environment. This robotic maintenance system is operated by a teleoperated control which was designed to perform the nozzle dam maintenance tasks in a remote manner without endangering the human workers. Specific maintenance tasks involve the transportation, insertion, and removal of nozzle dams in a water chamber inside a steam generator via a narrow man-way entrance port. The developed robotic maintenance system has two major subsystems: a two degrees of freedom guiding device acting as the main guiding arm and a master-slave manipulator with a kinematic dissimilarity. The mechanical design considerations, control system, and capabilities of the robotic maintenance system are presented. Finally, a graphical representation of the nozzle dam maintenance processes in a simulated work environment are also demonstrated.

Keywords: Nozzle dam operation, master-slave manipulator, remote maintenance, teleoperation

1. INTRODUCTION

The Kori nuclear power plant in Korea is a pressurized water reactor (PWR) four-unit nuclear power station operated by Korea Electric Power Corporation. The Kori Unit No. 1 which is a two-loop, 600 Mwe plant of the Westinghouse design started its first operation in 1978. The steam generators in Unit No.1 are the Westinghouse model constructed with numerous thin tubes made of Inconel 600. The steam generator tubes during an operation are subject to multiple stresses, vibrations, and various types of corrosion that tend to shorten the tubes' service lives. These tubes require a periodic maintenance to keep them in service during the plant overhaul period. Tube maintenance work conducted at the water chambers inside the steam generator include diagnostic tests to identify the locations of degradation along the tubes, and a repair process to remedy the damaged tubes for the operation and safety of the facilities. Such maintenance tasks are performed during the period of plant refueling in order to reduce the operating time and improve its productivity.

Prior to plant refueling, the reactor vessel that is connected to the nozzles of the water chamber via pipes is filled with water as a shield from the radiation emitting from the core section. It causes the filled water to flow into the water chambers via pipes because of the level difference between the water chamber and the reactor vessel, and thus makes the tubes maintenance process impossible. The important initial step in the steam generator tubes maintenance is the nozzle dam insertion because the tube inspection and repair process can not begin until the flow of the contaminated water from the reactor vessel into the water chamber is completely prevented. Dam insertion is typical of the complex tasks because of the structure of the water chamber and it requires an excessively careful preparation because of irradiation and contamination. Currently, the dam insertion operations are performed either by human beings or by mechanical means, with a resulting potential for contaminating the workers. A highly robotized system, therefore, will have to be used to minimize the personnel radiation exposure and to contamination potential and increase its productivity [1].

The Advanced Robotics Laboratory at Korea Atomic Energy Research Institute (KAERI) [2] developed a robotic maintenance system for the nozzle dam applications at the Kori Unit 1 nuclear power plant in Korea. This robotic maintenance system which is remotely controlled from a remote control site was designed to perform the nozzle dam maintenance tasks quickly and efficiently, thereby improving the safety and protecting the personnel. Specific tasks involve transporting dams into the water chamber through a narrow manway entrance port with a diameter of 45 cm, inserting them into nozzle, screwing them on to the nozzle, and removing them back to the water chamber exterior after completing the tube maintenance work.

In the subsequent sections, we describe the overall design considerations, features, and the control system of a robotic maintenance system for the nozzle dam transportation, insertion, and removal operations. We also demonstrate a graphical simulation of the nozzle dam maintenance process in a simulated work environment.

2. SYSTEM DESCRIPTION

2.1 System overview

A robotic maintenance system for the nozzle dam operations consists mainly of a guiding device, a slave manipulator, input device, and a human operator. Fig. 1 shows the functional connection of the robotic maintenance system. An operator located at the control site controls both the guiding device and the slave in the remote working environment by moving the input devices. The guiding device mounted on the manway frame of the water chamber carries the slave and moves it into the water chamber. Then, the slave, which has a redundant linear motion at its base due to the guiding device, moves its tool to various locations within a localized area of the water chamber, accepts dams at predetermined positions, and installs them into the nozzle or removes them from the nozzle.

An operator is included in the control loop of the nozzle dam maintenance process because he or she monitors and maps the operations of the guiding device and the slave through a video surveillance. Two cameras are used to supervise the maintenance operations. One which is attached to the interior of the water chamber monitors the maintenance environment, and the guiding device and the slave operations. The other attached at the center of the tool of the slave observes the contact between the tool and the environment and the locations of the connecting holes made on the nozzle as well as the locations of the bolts suspended on the dams.

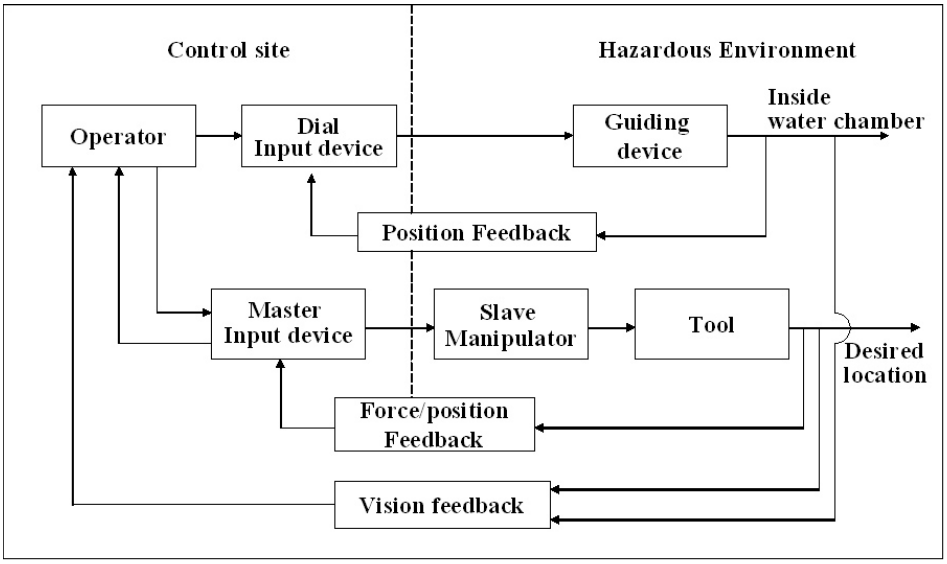


Fig. 1 Block diagram of the robotic maintenance system for the nozzle dam operation.

2.2 Design considerations

The design concept of the robotic maintenance system includes all the mechanical, electrical, hydraulic, and system integration elements required to produce a fully functional system and to be radiation-tolerant thus avoiding possible damages due to irradiation and contamination at the work environment. The slave manipulator shown in Fig. 2 was designed to have a payload capacity to carry the nozzle dam (about 15 kg) at the end-effector, a resolution of about 0.3 mm on all the axes for a fine positioning of the end effector and a rigidity for the process forces. As shown in Fig. 3, the input device for the slave was designed to allow the operator to feel the contact with the remote task environments and reduce the physical and mental burdens during the operations. The guiding device was designed to carry the slave, move it inside the water chamber, and serve as its support.

The configuration of the slave is designed with a 6 dof hydraulic manipulator, which is a modified Schilling Titan 2.5 version. The slave provides a higher lift capacity than that normally available for a teleoperation with 60 kg in an elbows-out configuration at the maximum extended reach of 195 cm. The body of the slave is made of Titanium. Onboard electronics provide a power and control signal distribution, and reduce the volume of the signal and power cables to the slave for communicating with the operator's station. A hydraulic power supply and valve system provides power to the slave and driving actuators. The master as an input device for the slave is a 6 dof electrically driven universal force reflecting interface device that is dissimilar kinematically from the slave. The reaction force generated from the slave interacting with external objects or a surface could be transferred back to the operator. This configuration permits the designing of a high performance device tailored to the operator's local environmental geometry and provides a convenient platform for which the multiple control strategies can be implemented [3-4].

The guiding device acting as the main guiding arm consists of lower and upper links, which are connected through revolute and prismatic joints in sequence. This device is made of CFRP (Carbon Fiber Reinforced Plastic) because of its light weight and high stress level. The base of the rotary mechanism is firmly fixed to the manway frame outside the water chamber.

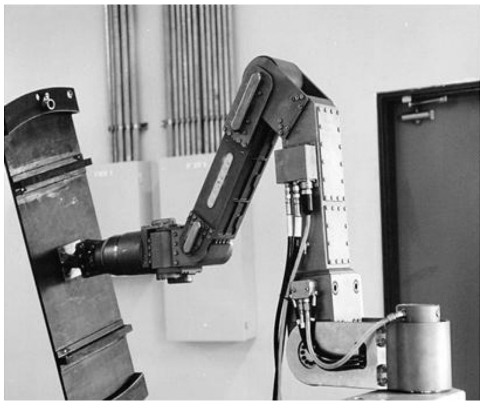


Fig. 2 The 6 DOF slave manipulator.

Fig. 3 Generalized master manipulator.

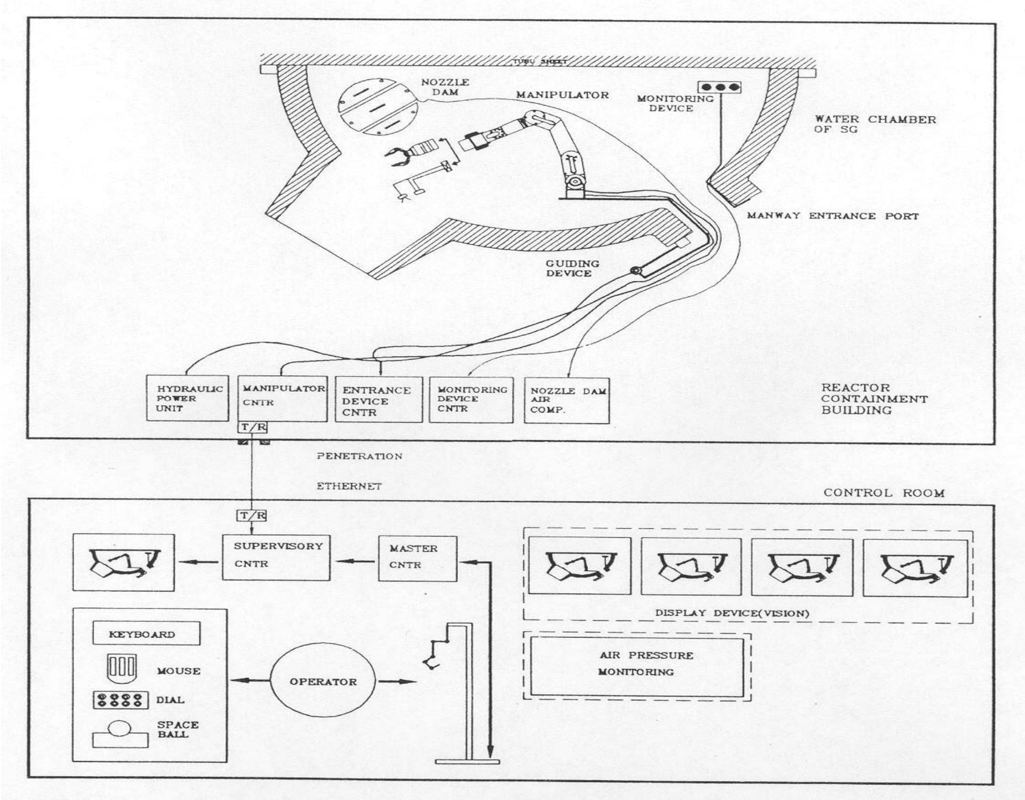


Fig. 4 The schematic representation of the control flow for the robotic maintenance system.

The rotary motion puts the slave mounted on the base plate of the linear mechanism into the water chamber via a narrow entrance port. The translational motion guides the base of the slave to the desired locations. This configuration provides the slave the more maneuverability and an extended workspace by adding a redundant dof. The tools are electrically driven devices, which are designed and fabricated to grasp the nozzle dam, and tighten and loosen the bolts. These tools have modular features for an easy installation and removal on the wrist frame of the slave.

3. CONTROL SYSTEM

The mechanical portion of the robotic maintenance system consists of the geometry that allows the slave and the guiding device to move and apparatus by which the power is transformed to the geometry. The electronics bring the signals to the slave, guiding device, and camera unit and provide the power in the drive actuators.

Fig. 4 shows the functional connections of the modular control structure for the robotic maintenance system. The control center is the human interface between the robotic maintenance system and the work environment. The control center provides a control location for the system and is located at a remote site for from the work environment of the water chamber of the steam generator. As shown in Fig. 5, the control console comprises of an operator-friendly control panel, viewing system monitors, tool controls, and input devices. It combines the hard controls for the primary motions of the devices at work site with the input devices for their secondary and auxiliary functions at the control site.

The robotic maintenance system is powered and controlled via a tether. This form of power and control was selected because powering a system via a tether allows for reliable

Fig. 5 The control console located in an operating area.

operations of an unlimited duration and eliminates the need for ventilated batteries. Transmission of the control and video signals through a tether ensures a reliable control of the system, regardless of the remote distance between the operated system and the operator.

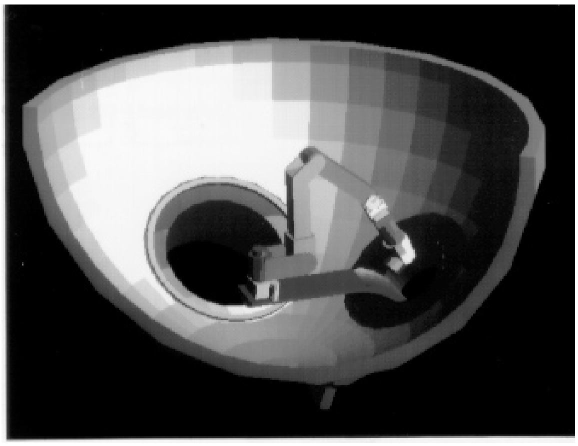


Fig. 6 The combined graphical models of the water chamber, slave manipulator and guiding device.

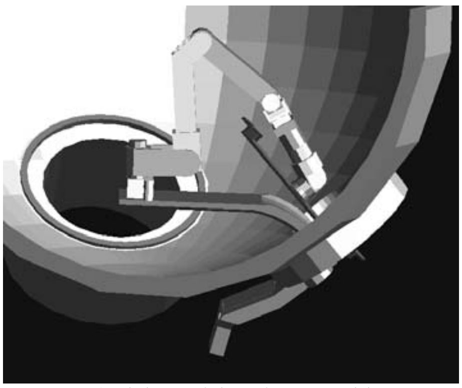
Both manual and teleoperated control modes are available to the operator who interacts with the system via a dial and master or space ball. The guiding device is controlled via a dial input device. The teleoperation of the slave through a master or space ball input device is handled in a Cartesian rather than joint space control because of its advantages for a non-replica master/slave system [5-7]. The space ball is used to control a 6 dof: 3 dof for the position control and 3 dof for the orientation control. The default of the keyboard control is always present as a backup control.

Control and sensor communications for all the parameters of the robotic maintenance system are managed through a VME bus card and electronics module. The onboard controller and console software run on a VME-based 68040 Motorola CPU under a VxWorks real-time control architecture. One CPU handles the controls of the slave, guiding device, as well as the monitoring device. The other is used for the master controller and the operator interface. The onboard software is responsible for communicating with the console, monitoring all the onboard sensors, and controlling all the onboard actuators. The console software is responsible for monitoring the visual display and all additional hardware devices (e.g., dial, space ball, and master) at the console panel and sending the console information to the onboard software. The two systems communicate through Ethernet.

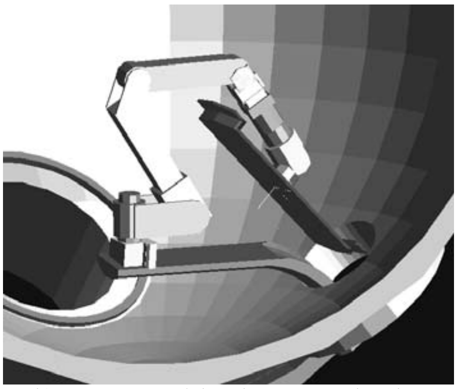
4. SIMULATION

Once a robotic maintenance system design has been established, it is possible to start the detailed path planning process. This can be achieved by using the graphics system in conjunction with the supervisory computer and the geometric controller. The nozzle dam insertion and removal strategies such as the dam pickup, movement, placement, bolting and unbolting can be investigated and optimized via a graphic simulation.

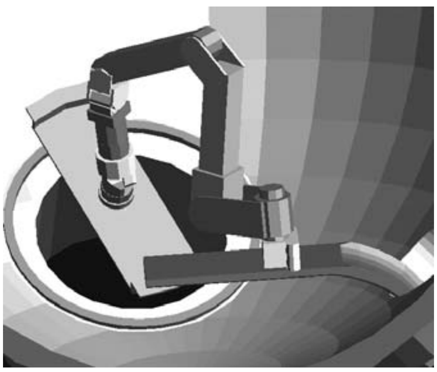
As shown in Fig. 6, the graphical models of the slave manipulator, guiding device, monitoring device and water



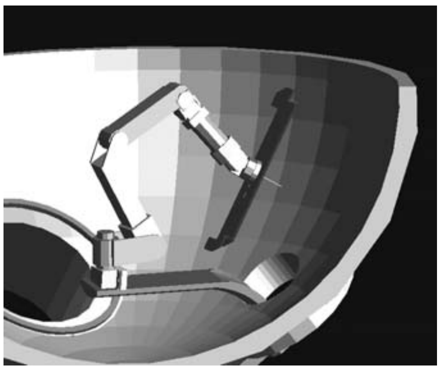
a) pickup of dam from outside



b) movement of dam into water chamber



c) insertion of dam onto nozzle



d) removal of dam from nozzle

Fig. 7 The graphical simulation of the nozzle dam insertion and removal process.

chamber was developed and integrated to simulate the conceptual design, detailed path planning, and rehearsal support by use of the 3D modeling package in ROBCAD. Fig. 7 shows the sequence of the nozzle dam insertion and removal process in a graphic environment.

5. CONCLUSIONS

The use of teleoperated machines or robotics has been treated as essential elements for the solution of human safety problems in nuclear power plants. One of the many maintenance aspects to be considered is the insertion and removal of the nozzle dam in the water chamber of the steam generator. The robotic system developed in this work has shown its maintenance applications for the nozzle dam operations in hazardous environments. The significance of the developments is the provision of a robotic system that can be operated from remote locations to perform the nozzle dam insertion/removal tasks efficiently and without endangering the human workers. Nozzle dam maintenance using this system has the benefits of on improved worker safety, reduced personnel exposure dose rate, and a reduced operating time and cost.

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REFERENCES

[1] C. J. H. Waston, "Remote Handling Technology for the Nuclear Industry: Recent Development at Harwell," *Proceedings Remote Techniques for Nuclear Plant Conference*, Strtford-upon-Avon, pp. 16 - 23, 1993.

[2] KAERI Report, "The Development of Robotic System for the Nuclear Power Plant," KAERI/RR-1508/94, Daejeon, Korea, pp. 589, 1994.

[3] H. Das, H. Zak, W. S. Kim, A. K. Bejczy, and P. S. Schenker, "Operator Performing with Alternative Manual Control Modes in Teleoperation," *Presence*, vol. 1, no. 2, pp. 201 - 217, 1992.

[4] G. Hirzinger, J. Heindl, and K. Landzettel,"Control Structure in Sensor-Based Telerobotic Systems," *Proceedings IEEE Conf. Robotics and Automation*, pp. 267 - 276, 1991.

[5] K. Kim, S. Kim, and J. K. Salisbury, "Development of Highly Dexterous Manipulation Techniques for Nozzle Dam Insertion Application," *Proc. of the 10th Korea Automatic Control Conference*, Seoul, Korea, Vol. 2, pp. 1150 - 1153, 1995.

[6] A. K. Bejczy and J. K. Salisbury, "Controlling Remote Manipulator through Kinesthetic Coupling," *Computers in Mechanical Engineering*, vol.1, pp. 48 - 60, 1983.

[7] T. F. Chan, R. V. Dubey, and M. W. Noakes, "Generalized Bilateral Control for Dissimilar Kinematic Teleoperators and Application to D&D Type Tasks," *Proceedings ANS 6th Topical Meeting on Robotics and Remote Systems*, Calif., USA, vol. 1, pp. 281 - 284, 1995.