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The Design of Nozzle-Dam Work Robot in Steam Generator

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Abstract

In this paper, we are design an 8-axes robot arm and simulate a path to work on the mounting and dismounting of a nozzle-dam in the steam generator of a nuclear power plant. We will use 3-D modeling and structural analysis in the simulation. We will suggest location compensation algorithm for accurate positioning and collision avoidance of work robot. Also, we are design a robot control system for the servo motor drive. Through a test using the prototype robot, we will confirm that our robot will perform mounting and dismounting of nozzle-dam within the target time well.

Keywords: *Nozzle-dam, steam generator, nuclear robot, nozzle-dam robot*

1. Introduction

The nozzle-dam is a special closure that block the coolant flow from reactor at the inlet and outlet nozzles in the steam generator of a nuclear power plant [1]~[4]. The Mounting and dismounting of a nozzle-dam is an essential process for inspection and maintenance in the steam generator [5]~[9]. Currently, any work inside of the steam generator water chamber requires manpower, which will inevitably expose the worker to high levels of radiation during overhaul. Generally, 12 workers are assigned to a steam generator in secondary loop. Although their exposure does differ by the type of job that they have, they are supposed to be exposed to 18~36 Sievert of radiation at each unit. Therefore, multiple simulation exercises are needed for the workers. However, it is difficult to manage the required number of workers with abundant experience. Moreover, there is always a high probability of human error since very narrow space is allowed to work inside of a water chamber under the high level of radiation. To eliminate these problems, any working robots are required to replace the workers [10][11]. In this paper, we have designed an 8-axes robot arm and simulated a path to work on the mounting and dismounting of nozzle-dam in the steam generator of nuclear power plant. We will use 3-D modeling and structural analysis in the simulation. We suggest location compensation algorithm for accurate positioning and collision avoidance of work robot. Also, we have designed robot control system for servo motor drive. Through a test using the prototype robot, we have confirmed that our robot will perform mounting and dismounting of nozzle-dam within the target time well.

2. The Environment for the Nozzle-Dam Working

Steam generators are heat exchangers used to convert water into steam from heat produced in a nuclear reactor core. They are used in pressurized water reactors (PWR) between the primary and secondary coolant loops. Most American, Canadian, Japanese, French, and German PWR suppliers use the vertical U-tube design with inverted tubes. The vertical steam generators generally have a feed water ring supply header on the outer edge of the steam generator. Figure 1 shows

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an overview of the vertical steam generator. The nozzle-dam is used to block the coolant flow from the reactor at the inlet and outlet nozzles in the steam generator of a nuclear power plant. Figure 2(a) shows the nozzle-dam in steam generator and figure 2(b) shows a 3-D drawing model that was cut from the bottom of the steam generator. The average weight of a nozzle-dam is about 30 kg.

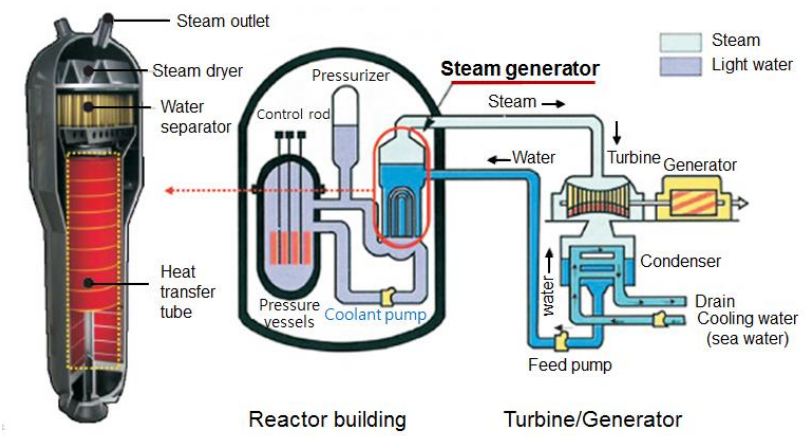
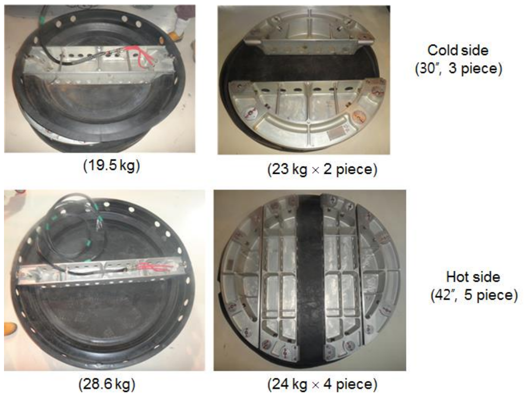
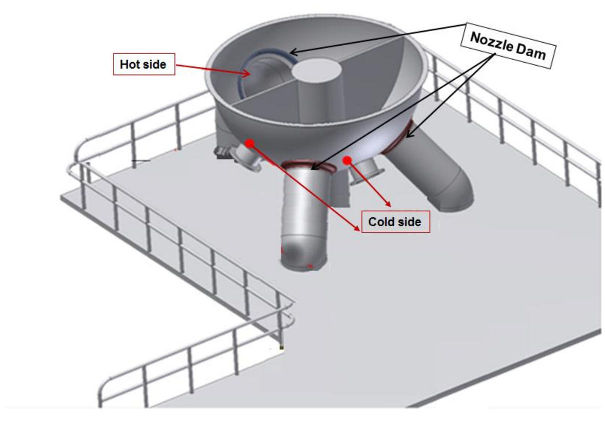


Figure 1. Overview of Steam Generator in Nuclear Power Plant System



(a) Nozzle-dam



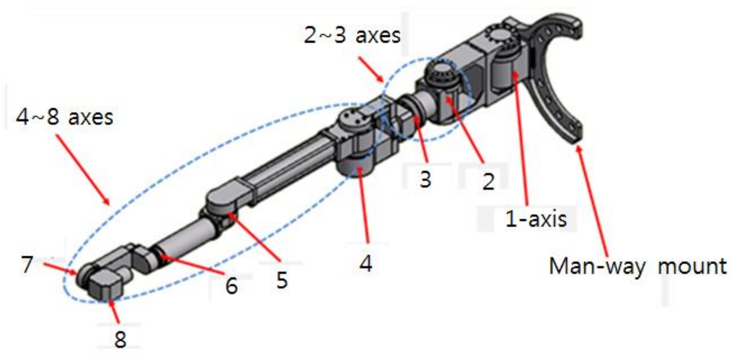
(b) 3-D drawing model

Figure 2. Cross-Sectional Area of Nozzle-Dam in Steam Generator

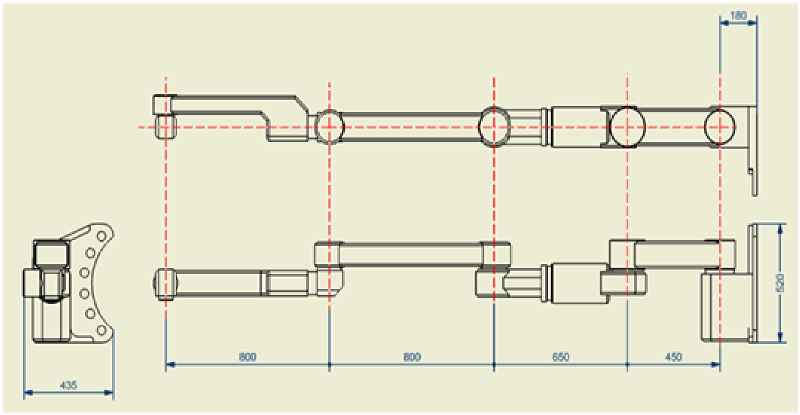
The diameter of a nozzle-dam is 30 inches on the cold side and 42 inches on the hot side. The nozzle-dam consists of 3 pieces (segments) in the cold side, and 5 pieces (segments) in the hot side.

3. The Design of 8-axes Jointed-Arm Robot

The robot should move to the man-way hole where workers enter and exits. The diameter of this man-way hole is about 18 inch. Therefore, the radial movement of the robot is very limited. In view of these points, we looked to the simulation work on various routes. We have designed a robot-arm with four-modules (attitude determination module, location determination module, segment module, and man-way flange mounted base operation module) for easy transport, fast assembly and simple installation. We have reduced the weight of each module to less than 30 kg. Also, we have designed a robot as a serial-type multi-joint structure to eliminate interference. The cover and tool of a nozzle-dam are put over the entrance of the man-way. To calculate the dimension and joint length of the robot-arm, we have performed 2D and 3D solid works simulation.



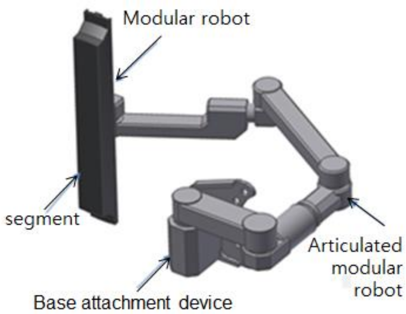
(a) 8-axes robot arm modeling



(b) Detailed design drawings

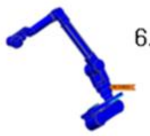
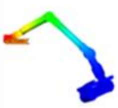
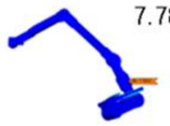
Figure 3.The Design of 8-axes Joint Arm Robot

We have performed structural analysis about the design model of the robot-arm. In the first step, we generate mesh model (node numbers: 116,362 nodes / tetra: 67,478 elements). In the second step, we have set 3-analysis positions (initial position, middle position, final position). In the next step, we find a minimum safety factor point and displacement size using these three positions. Through the structural analysis, we obtained maximum displacement and minimum safety values of the 3 analysis positions. The ″maximum displacement/ minimum safety″ values of the initial position, middle position, and final position are 2.46mm/10.9, 4.48mm/6.69, and 5.23mm/7.78, respectively. From these data, we concluded our design model is safe. Figure 4 shows the results of structural analysis of the detailed design model. Figure 4(a) is the design mode of the robot-arm and figure 4(b) is its mesh model. Figure 4(c) is the result of structural analysis.



(a) Design model

(b) Mesh model

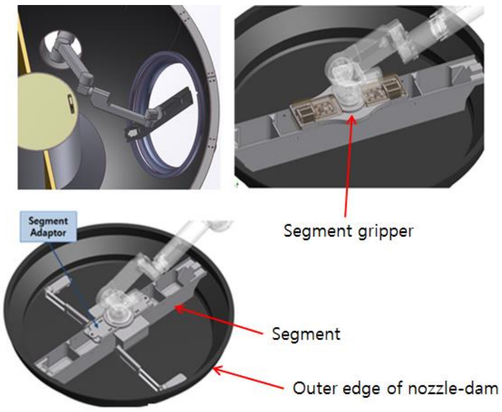
Position	Analysis shape	Full Displacement (Max.)	Safety(Min.)
Initial Position		 2.46 mm	 10.9
Middle Position		 4.48 mm	 6.69
Final Position		 5.23 mm	 7.78

(c) Structural analysis results

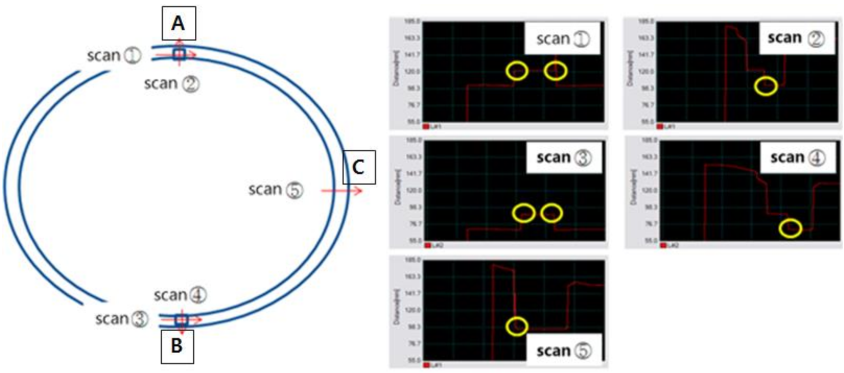
Figure 4.The Results of Structural Analysis of the Detailed Design Model

4. Location Compensation Algorithm

The man-way mount of the joint-arm robot is used to the fix robot arm to the man-way pipe. The variation of mounting points leads to errors in the moving trajectory of the robot gripper. In this paper, we propose the location compensation algorithm to compensate the trajectory error of the robot arm which is associated with variation of mounting points. The laser distance measurement sensors are mounted in the segment gripper. These sensors will measure the distance between nozzle-dam mounting segment and gate circle-hole which will be installed nozzle-dam. These sensors collect the following 3-points location information: upper and lower grooves information of gate circle-hole, side location information of gate circle-hole, and center and slope information of retention ring. Figure 5 shows the concept of the location compensation. In the first step, we find point A, B and C by scanning the distance measurement sensors (Scan 1 ~ Scan 5). Second, we produce one plane by connecting the 3-points, A, B, C and obtain the slope information. Third, we find the center point of gate circle-hole from the 3-points.



(a) Segment gripper and segment of nozzle-dam



(b) Scanning point of gate circle-hole

Figure 5. The Concept to the Location Compensation

The center point of the segment gripper is used to fix the segment gripper to the robot arm. Figure 6 shows the concept to find the center point of the segment gripper. In the first, we find the location of point P1 and P2 by the scanning the distance measurement sensor (Scan 1). In the second, we find location of point P3 by scanning sensor (Scan 2). The trajectory of ″Scan 2″ is perpendicular with line P1-P1 and pass by the center of line P1-P1. Point P3 is determined as a reference coordinate to fix segment gripper to the robot arm.

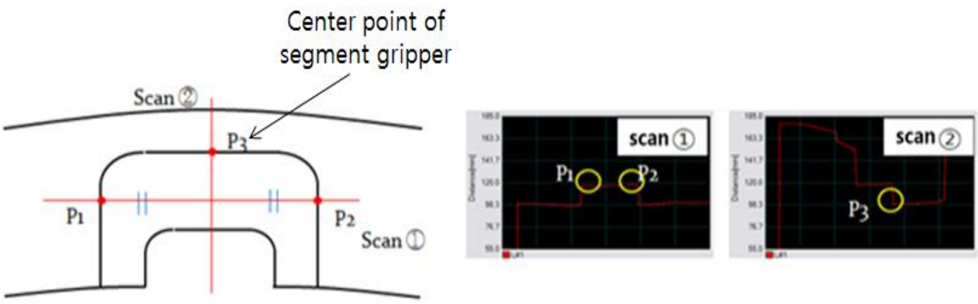


Figure 6. The Concept to Find Center Point of Segment Gripper

Figure 7 shows the concept to the find center point, P(x,y) of the gate circle-hole from the 3-points, A(x_1, y_1), B(x_2, y_2), C(x_3, y_3). Equation (1) is an equation to obtain the perpendicular bisector of the line segment A-B. Equation (2) is an equation to obtain the perpendicular bisector of the line segment B-C. Equation (3) is a matrix representation of equation (1) and (2). From equation (3), Center coordinates x and y can be obtained by equation (4).

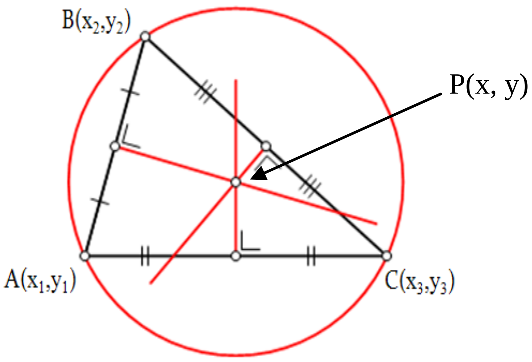


Figure 7. The Concept to Find Center Point of Gate Circle-Hole

$$(x_2 - x_1)\left(x - \frac{x_1 + x_2}{2}\right) + (y_2 - y_1)\left(y - \frac{y_1 + y_2}{2}\right) = 0 \quad (1)$$

$$(x_3 - x_2)\left(x - \frac{x_2 + x_3}{2}\right) + (y_3 - y_2)\left(y - \frac{y_2 + y_3}{2}\right) = 0 \quad (2)$$

$$\begin{pmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_2 & y_3 - y_2 \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} = \frac{1}{2}\begin{pmatrix} x_2^2 - x_1^2 + y_2^2 - y_1^2 \\ x_3^2 - x_2^2 + y_3^2 - y_2^2 \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} x \\ y \end{pmatrix} = \frac{1}{2} \begin{pmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_2 & y_3 - y_2 \end{pmatrix}^{-1} \begin{pmatrix} x_2^2 - x_1^2 + y_2^2 - y_1^2 \\ x_3^2 - x_2^2 + y_3^2 - y_2^2 \end{pmatrix}$$

$$= \frac{1}{2[(x_2 - x_1)(y_3 - y_2) - (y_2 - y_1)(x_3 - x_2)]} \begin{pmatrix} y_3 - y_2 & y_1 - y_2 \\ x_2 - x_1 & x_2 - x_1 \end{pmatrix} \begin{pmatrix} x_2^2 - x_1^2 + y_2^2 - y_1^2 \\ x_3^2 - x_2^2 + y_3^2 - y_2^2 \end{pmatrix} \quad (4)$$

5. Design of Servo Motor Driver System

We have designed a servo motor drive interface system to control the motion of robot arm. The NI Compact RIO (cRIO-9065) is a real time processor for communication with servo-driver interface system and to the control of servo motors. The NI servo motor drive (MID-7654) can control the 8-axes of the robot arm. Also, NI Compact RIO has two Ethernet ports for the direct connection with GigE camera. Analog and digital input/output card are attached to the NI Compact RIO to measure and control analog and digital sensor devices. Figure 8 shows the NI servo-motor drive interface system for the robot-arm control. This system is the local control module of a nozzle-dam work robot. In our research, we have designed another servo drive interface system. These systems have eight servo drives connected with 8-axes motor units.

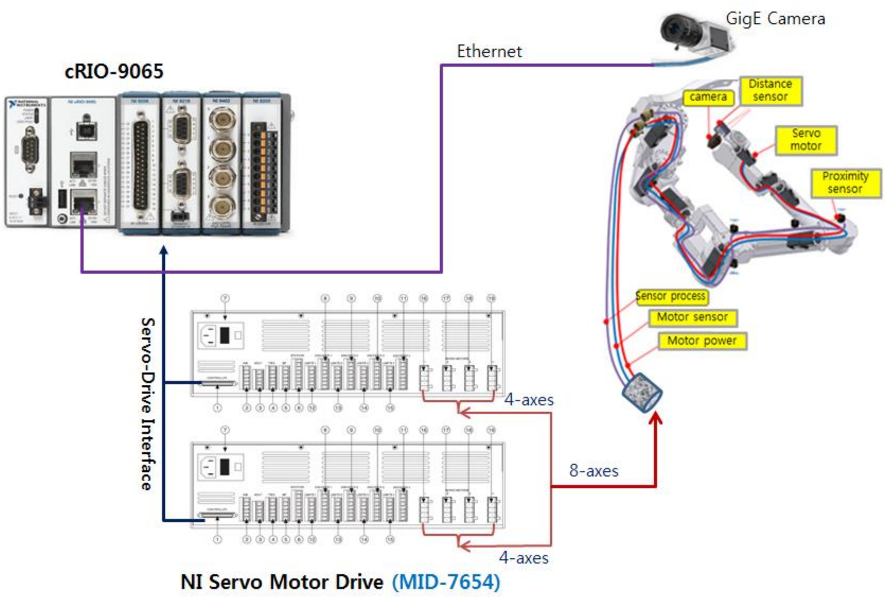
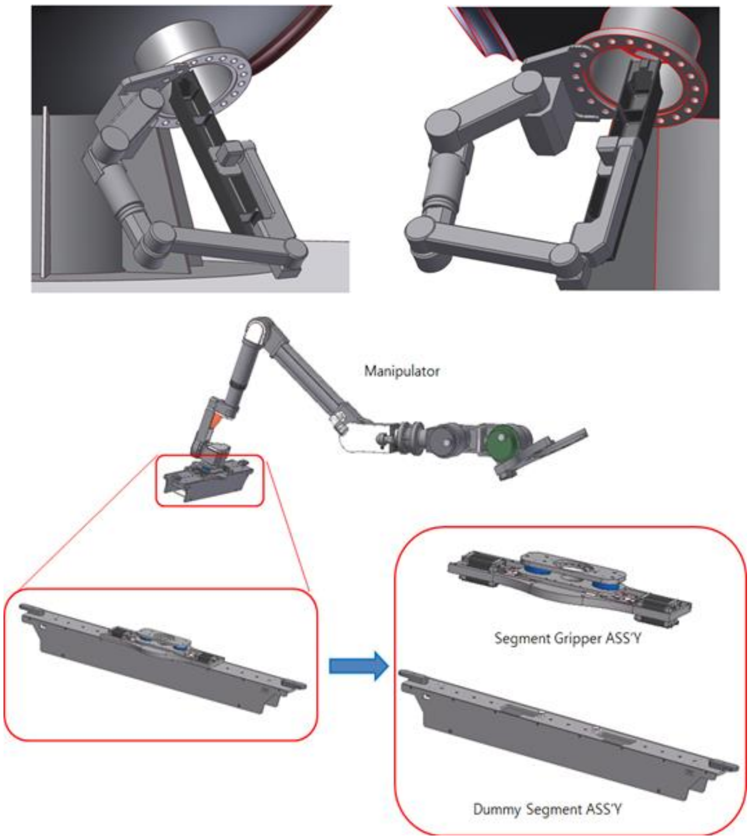


Figure 8. The Servo Motor Drive Interface System for the Robot-Arm Control

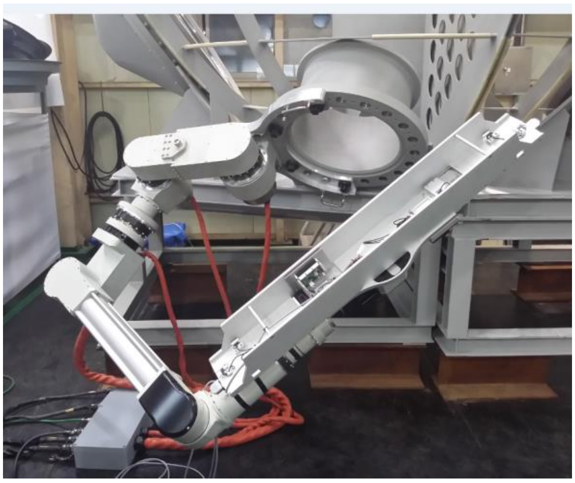
6. Test of Nozzle-Dam Work Robot

In this paper, we have designed an 8-axes robot arm. For accurate positioning and collision avoidance of the work robot, we have simulated via 3-D modeling. The modeling factors are nozzle-dam weight (maximum 30kg per each segment) of the cold side and hot side, diameter of the cold side (30 ″) and the hot side (42 ″), diameter of the man way hole (18 ″). For the experiment, we have developed a prototype model of nozzle-dam work robot. Figure 9(a) shows 3-D simulation model, and figure 9(b) shows a prototype model of nozzle-dam work robot. The segment of segment-gripper in figure 9(b) is a dummy segment that was made for the testing.

The weight of the dummy segment is 30kg. Figure 10 shows segment test image of the nozzle-dam work robot

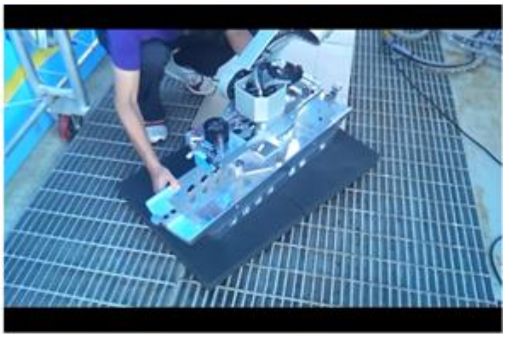


(a) 3-D simulation model



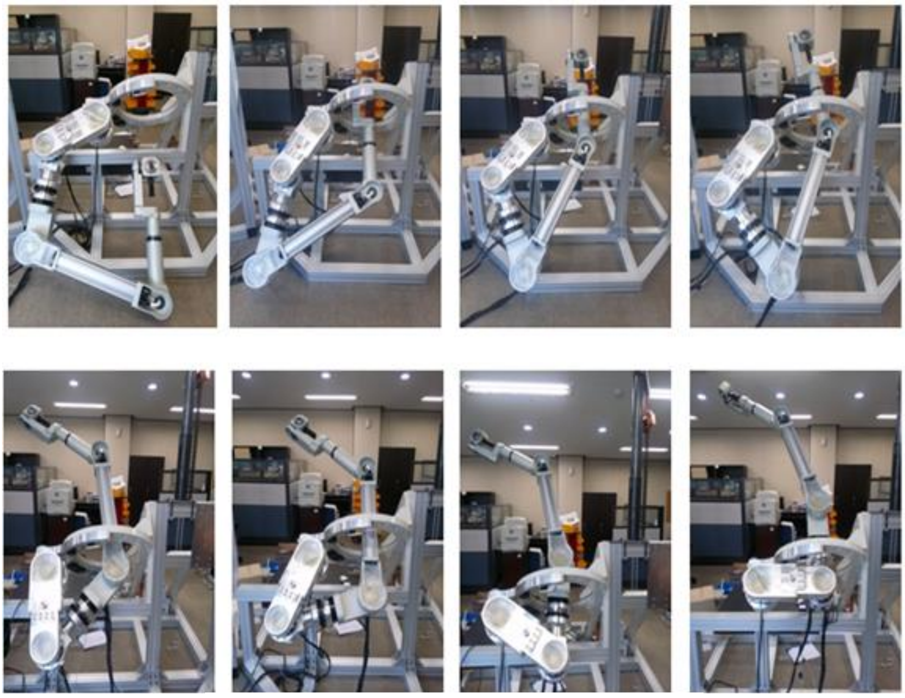
(b) Prototype model

Figure 9. Test Model of the Nozzle-Dam Work Robot



(a) Auto scanning test before install of segment

(b) Auto scanning test after install of segment



(c) Segment mounting test based on way-point

Figure 10. Segment Test of the Nozzle-Dam Work Robot

7. Conclusions

In this paper, we have designed an 8-axes robot arm and simulated path to work on the mounting and dismounting of the nozzle-dam in the steam generator of a nuclear power plant. We have proposed a location compensation algorithm to compensate the trajectory error of the robot arm which is associated with a variation of mounting points. For the trajectory simulation, 3-D modeling and structural analysis were performed. We have developed a prototype model of a nozzle-dam work robot for the test. Through the test, we have confirmed that our robot perform mounting and dismounting of nozzle-dam within the target time well. In the future, we will continue the reliability test after complemented the systems.

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