Development of a Nuclear Steam Generator Tube Inspection/maintenance Robot

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Abstract: This paper presents a nuclear steam generator tube inspection/maintenance robot system. The robot assists in automatic non-destructive testing and the repair of nuclear steam generator tubes welded into a thick tube sheet that caps a hemispherical or quarter-sphere plenum which is a high-radiation area. For easy carriage and installation, the robot system consists of three separable parts: a manipulator, a water-chamber entering and leaving device for the manipulator and a manipulator base pose adjusting device. A software program to control and manage the robotic system has been developed on the NT based OS to increase the usability. The software program provides a robot installation function, a robot calibration function, a managing and arranging function for the eddy-current test, a real time 3-D graphic simulation function which offers remote reality to operators and so on. The image information acquired from the camera attached to the end-effecter is used to calibrate the end-effecter pose error and the time-delayed control algorithm is applied to calculate the optimal PID gain of the position controller. The developed robotic system has been tested in the Ulchin NPP type steam generator mockup in a laboratory.

Keywords: steam generator, tube inspection robot, automatic non-destructive test, robot calibration

1. INTRODUCTION

Steam generators(SG) of a nuclear power plant are heat exchangers which are internally in contact with primary coolant and externally in contact with the secondary coolant which is then vaporized. The steam generators separate the primary side from the secondary side through several thousand tubes ranging from 20 to 40m in length. Each tube is 1 to 2 cm in diameter with a wall thickness of ~1mm. The tubes are welded into a thick tube sheet that caps a hemispherical or quarter-sphere plenum. The integrity of the relatively thin tubing can therefore influence the degree of radioactive contamination appearing on the secondary side in the case of tube leaks. Therefore the inspection and maintenance of the steam generator tubes are very important from the view point of integrity. Eddy-current testing (ECT), a nondestructive evaluation (NDE) technique, is used to evaluate the integrity of the tube-pressure boundary. Practically all the work must be performed robotically because the plenum is a high-radiation area. A robotic arm with a precise positioning capability must enter the plenum through a 40-cm passageway.[1-3]

NPP shutdowns are done on an outage schedule which occurs roughly once a year for the purpose of inspection, maintenance, and repair. ECT for SG tubes is usually performed during the outage. The planned outage normally has a critical time schedule of four to six weeks. Any downtime beyond the planed schedule can cost a utility company a quarter of a million dollars each day due to the lost power generation. If an NPP has a shutdown due to a leak of radiation caused by defective tubes, the cost could escalate to 10 to 100 million dollars.[4] In order to avoid an accidental shutdown or exceeding the scheduled outage, the inspection and repair process must be both efficient and sufficiently accurate. There have been numerous research works for the automatic inspection and the automatic repair of SG tubes. [5-6]. SM series of Zetec are SG tube inspection robots which are not usually used to repair SG tubes due to their flexibility. And ROSA series of Westinghouse are SG tube repair robots which are not usually used to inspection due to their weight and inconvenience.

In this research, a radiation hardened robot system is developed which assists in automatic non-destructive testing and the repair of nuclear steam generator tubes. And a control system is developed. For easy carriage and installation, the robot system consists of three separable parts: a manipulator, a water-chamber entering and leaving device of the manipulator and a manipulator base pose adjusting device. The kinematic analysis using the grid method was performed to search for the optimal manipulator's link parameters, and the stress analysis of the robotic system was also carried out for structural safety verification. The robotic control system consists of a main personal computer placed near the operator and a local robotic position controller placed near the steam generator. A software program to control and manage the robotic system has been developed on the NT based OS to increase the usability. The software program provides a robot installation function, a robot calibration function, a managing and arranging function for the eddy-current test, a real time 3-D graphic simulation function which offers remote reality to operators and so on. The image information acquired from the camera attached to the end-effector is used to calibrate the end-effector pose error and the time-delayed control algorithm is applied to calculate the optimal PID gain of the position controller.

Eddy-current probe guide devices, a brushing tool, a motorized plugging tool and a U-tube internal visual inspection system have been developed. A data aquisition system was built to acquire and process the eddy-current signals, and a software program for eddy-current signal acquisition and processing. The developed robotic system has been tested in the Ulchin NPP type steam generator mockup in a laboratory. The final function test was carried out at the Kori Npp type steam generator mockup in the Kori training center.

2. ROBOT SYSTEM

2.1 Robot design

A nuclear SG heat exchanger tube inspection/maintenance manipulator must be installed in the SG chamber without human worker's entering the SG chamber in order to avoid exposing them to harmful radiation. There are two non-entering manipulator installing methods. The first method is to mount a manipulator in the tube-sheet of the channel head of a SG. This method provides a more precise positioning. But it is not convenient to mount a manipulator. And there is the possibility of the fall of a manipulator. To avoid damaging the interior of the heat exchanger tubes, greate care is required. The second method is to mount a manipulator on a entering /leaving device fixed to the manway flange having a plurality of uniformly-spaced bolt holes. This method provides a quick installation of a robot system so that workers receive less doses of radiation. In addition to a manipulator mounting method, there are several considerations.

- determine a target nuclear steam generator
- convenience of usage to reduce a human doses of radiation
- easy moving and easy installation by two people
- exchangeability with conventional equipment
- withdrawal of a robot when the robot is out of order

A Ulchin NPP type (model 51B type) steam generator is selected for the target. We developed a 3D graphic model for the SG and a robot. Fig. 1 shows a developed heat exchanger tube inspection/ maintenance robot in the SG chamber. For easy carriage and installation, the robot is made up three separable parts: a manipulator, a water-chamber entering and leaving device of the manipulator and a manipulator base pose adjusting device.

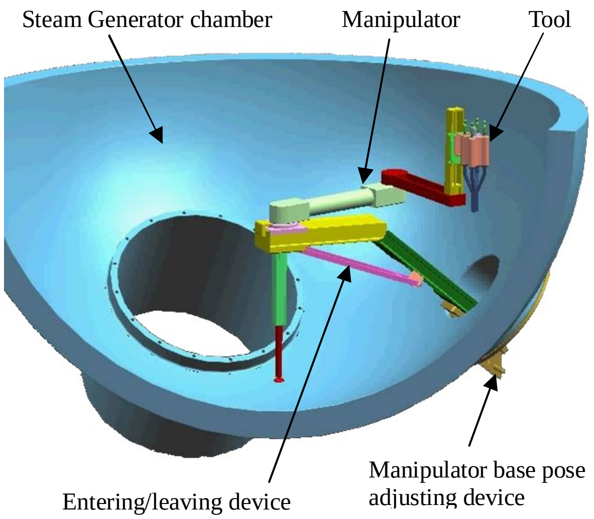

Fig. 1 Steam generator heat exchanging tube inspection/maintenance robot.

The manipulator base pose adjusting device fixed to the manway flange has two axes of movement, swing and roll to adjust the level of the manipulator base. The manipulator entering/leaving device slides and is then fixed to the swing plate of the base pose adjusting device.

The manipulator slides on the entering/leaving device through side rails and is then clamped at the top of the entering/leaving device. The upper part of the entering/leaving device is tilted to level off the robot base. The entering/leaving device has a supporting leg underneath the robot base. The supporting leg reduces the vibration when the robot arm is moving, and improves the rigidity to increase the accuracy.

The manipulator has two links which rotate on the horizontal plane, and a mast which moves in the z-axis direction. A inspection or a maintenance tool is connected to the mast. The manipulator positions the tool at the target tube. Once installed, the manipulator allows inspection and maintenance to be performed in a control room 100m away from a SG chamber to ensure operator safety.

2.2 Robot analysis

To calculate the driving torque of the tilting motor of the entering/leaving device, a kinematics' analysis is performed. Fig. 2 shows the schematic diagram of the entering/leaving device. It is noted that the upper part of the entering/leaving device is tilted by the linear motion q of a slider.

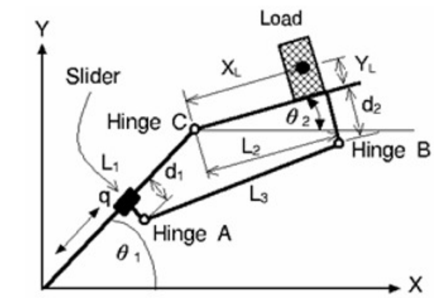

Fig. 2 Schematic diagram of entering/leaving device

When the velocity of the slider is 10 mm/sec, the acceleration of the slider is 5 mm/sec^2, the angle and angular velocity profile of the upper part of the entering/leaving device are obtained as in Fig. 3. It is noted that the required thrust force is about 560N from Fig. 3.

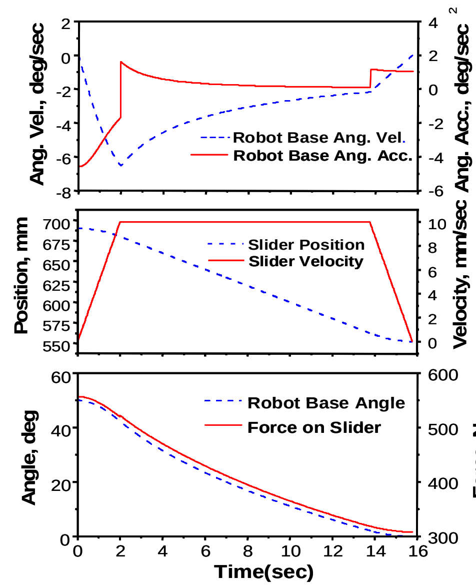

Fig. 3 Design parameter profile with slider velocity 10mm/sec and acceleration 5 mm/sec^2

To evaluate the integrity of the structure of the entering/ leaving device and the manipulator, FEM analysis is carried out with a commercial package Design Star. To analyze the maximum stress and maximum deflection, several assumptions are included.

- The manipulator pose adjusting device is rigid. And the entering/leaving device is rigidly fixed to it.
- The robot system is made of aluminum alloy for a light weight design.
- Motors, gear boxes mounted in the joints, the mast, inspection/maintenance tool are considered as a lumped mass.

The straight pose of the manipulator gives a maximum load to the structure. The analysis is carried out for the shoulder angles 0° and 90° . Fig. 4 shows the stress distribution. The arrows represent the lumped mass, gravity condition and constraint.

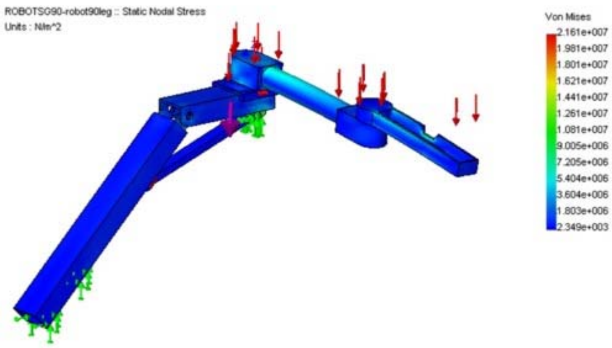

Fig. 4 Stress analysis with the shoulder angle 90° .

Table 1 shows the result of FEM analysis. The result shows the pose with a shoulder of 90° has a maximum stress and improves the integrity of the robot structure.

Table 1. The results of FEM analysis.

	Shoulder angle 0°		Shoulder angle 90°	
	w/o leg	with leg	w/o leg	with leg
Safety factor	2.89	3.74`	2.192	2.55
Max. deflection (mm)	5	1.97	4.93	2.25

2.3 Robot control system

To remotely control the robot system, the robot control system consists of four parts: a robot system, a controller box, main control computer, a video/audio system. Fig. 5 shows the remote robot control system.

Fig. 5 Remote robot control system.

The robot system is installed in the SG head mockup. The mockup is the Ulchin NPP SG type which has 1.28" pitched 3,330 heat exchange tubes. The mockup has about 200 tubes for ECT tests and brushing tests, and two tube sheet blocks for plugging tests. BLDC motors are used as the actuators of the robot due to their high efficiency. Resolvers are used as position sensors because resolvers has stronger resistence to radiation than the encoders usually used for motor position sensors.

Servo motor drivers, a motion controller, home sensor amplifiers, power supplies, a level sensor amplifier, limit sensor I/O ports and a LAN hub are enclosed in a controller box. The controller box placed near the SG designed for water-proof and vibration-proof.

An industrial PC with NT based OS is used as a main control computer for easy operation. The main control computer is located in a vehicle or a control room 100m away from a SG chamber, and mounted on the 19" rack. The main control computer communicates with the motion controller and an ECT data acquisition system (MIZ-43) through LAN cable.

A robot operator communicates with workers installing the robot system through a audio system, and is monitoring the state in and near the SG chamber through a video system. A digital recorder system records the work for the inspection and maintenance.

3. POSITION CONROL

3.1 Control gain tuning

PID gains of the motor drivers of the manipulator are tuned systematically with a time delay control (TDC) method.[9] Fig. 6 shows a block diagram of a PID control imbedded in the Tamagawa motor drivers.

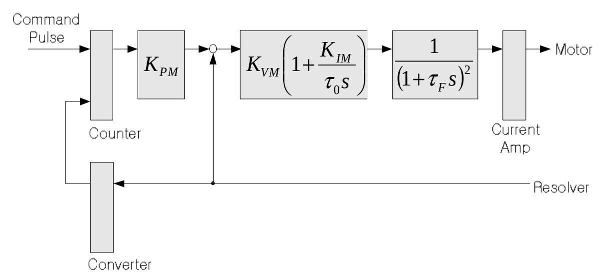

Fig. 6 Block diagram of the PID control of the driver.

The input torque of the motors calculated from the block diagram.

$$\tau(s) = -\left(K_{PM}E(s) + V(s)\right)K_{VM}\left(1+\frac{K_{IM}}{\tau_0 s}\right) = -K_{VM}\left(K_{PM}+\frac{K_{IM}}{\tau_0}+\frac{K_{IM}K_{PM}}{\tau_0}\frac{1}{s}+s\right)E(s) \quad (1)$$

where, $E(s) = L(e(t)), V(s) = L(\dot{e}(t)), v_d = 0.$

The PID control gains of the Tamagawa driver are calculated as follows.

$$K_{PM} = \frac{K_D \pm \sqrt{K_D^2 - 4K_P}}{2}, \quad K_{IM} = \frac{\tau_0 K_P}{K_{PM}}, \quad K_{VM} = \frac{\overline{M}}{L} \quad (2)$$

where K_D and K_P are $n\times n$ diagonal matrices determined from error dynamics, $\overline{M}$ is a parameter determining the stability and performance of TDC and L is a sampling time of the control system.

Fig. 7 shows the control responses with the gains determined by the manual tuning and TDC method.

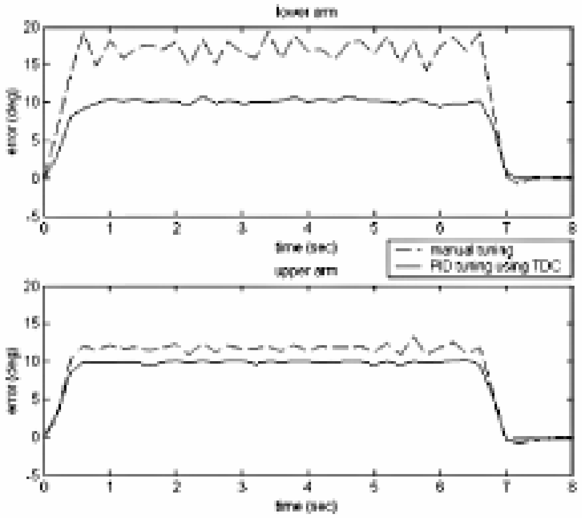

Fig. 7 Control responses with gain tuning.

It is noted that the proposed gain tuning method is not only systematic but gives better performance than the manual tuning.

3.2 Manipulator calibration

To insert an ECT probe in a heat exchange tube of 3/4" diameter, the inspection tool must be positioned at the target tube accurately. A mathematical model of the manipulator gives joint displacements for the corresponding pose of the tool. But there exist errors because the base point of the manipulator is changed when the manipulator is installed and there are deviations between the mathematical model used in the controller and the actual arm geometry. To reduce the errors, the mathematical model must be modified to match the robot, which is a manipulator calibration.

The manipulator must be calibrated with each installation, and calibrated again when the position error increases by some amount. Since there is no coordinate measurement machine in the SG chamber, the tube-sheet is set as a reference coordinate. Measured global coordinate data is obtained through the camera mounted on the tool and the robot control program.

The first step of calibration is to obtain a valid manipulator model. The Denavit-Hartenberg model is popular for modeling manipulator kinematics, but there are some problems in using this model for a calibration procedure. The most important limitation of the DH formalism is the treatment of consecutive revolute joints with nearly parallel axes, because constants in the transformations vary by large amounts in that case.[7] To solve the problem, a modified Denavit-Hartenberg model proposed by Hayati and Mirmirani is used for the consecutive parallel axes[8], which the homogeneous transformation matrix is

$$ {}^{n-1}\mathbf{A}_n = \begin{bmatrix} -s\alpha_n s\beta_n s\theta_n + c\beta_n c\theta_n & -c\alpha_n s\theta_n & s\alpha_n c\beta_n s\theta_n + s\beta_n c\theta_n & r_n c\theta_n \\ s\alpha_n s\beta_n c\theta_n + c\beta_n s\theta_n & c\alpha_n c\theta_n & -s\alpha_n c\beta_n c\theta_n + s\beta_n s\theta_n & r_n s\theta_n \\ -c\alpha_n s\beta_n & s\alpha_n & c\alpha_n c\beta_n & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (3) $$

If the mid point of the first row of the SG tubes is set for the base point, the coordinate frame assignment of the manipulator is shown in Fig. 8. It is noted that there are three parallel axes.

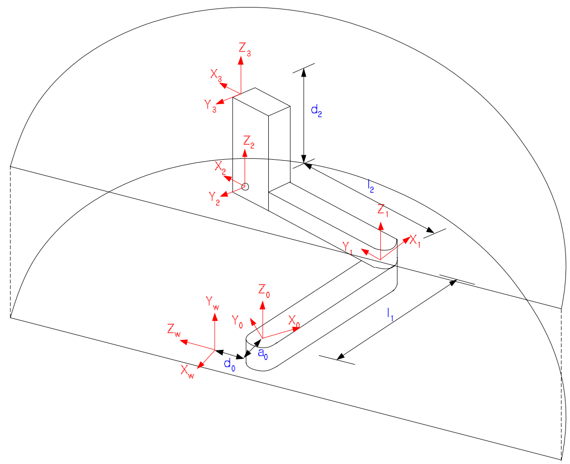

Fig. 8 Coordinate frame Assignment.

The transformation from frame B to frame 3 is

$$ \mathbf{T}_3 = {}^{B}\mathbf{A}_0 \, {}^{0}\mathbf{A}_1 \, {}^{1}\mathbf{A}_2 \, {}^{2}\mathbf{A}_3 . \quad (4) $$

Here, ${}^{0}\mathbf{A}_1$ and ${}^{1}\mathbf{A}_2$ are Hayati model.

The manipulator kinematic error model is expressed by the nominal value $\mathbf{T}_{3N}$ and $d\mathbf{T}_{3N}$ as follows.

$$ \mathbf{T}_{3N} + d\mathbf{T}_{3N} = \prod_{n=0}^{3} ({}^{n-1}\mathbf{A}_n + d\,{}^{n-1}\mathbf{A}_n) \quad (5) $$

Expanding Equation (5) and ignoring second-order product, a conventional Jacobian relation is obtained after some manipulation. The kinematic link parameters are identified by the linear least squares method. 8 tube holes are used for the calibration points. Table 2 shows the nominal values and identified values of the parameters.

Table 2 Kinematic link parameters of the manipulator.

Trans.	Type	θ	d	a	α
B→0	1	180 (180.083)	0.01 (0.083)	0.15 (0.198)	90 (89.2498)
0→1	2	0 (-2.943)	0(β) (0.993)	0.69 (0.702)	0 (0.2982)
1→2	2	-180 (-181.05)	-0.1(β) (-20.099)	0.84 (0.833)	0 (-25.862)
2→3	1	0	-0.001 (-0.0184)	0	0

Type 1 means the transformation of D-H model and type 2 that of Hayati model. Mean of error is about 1 mm.

3.3 Main control program

To carry out the inspection/repair works of SG tubes, a main control program is developed. A GUI based on the 3D graphics is developed to interface between the operators and the robot system. The control program consists of a setup mode, trunk setting mode, robot setting mode, calibration and manual mode, a scheduling and inspection mode.

Fig.9 shows the structure of the control program and Fig. 10 shows the GUI of the control program.

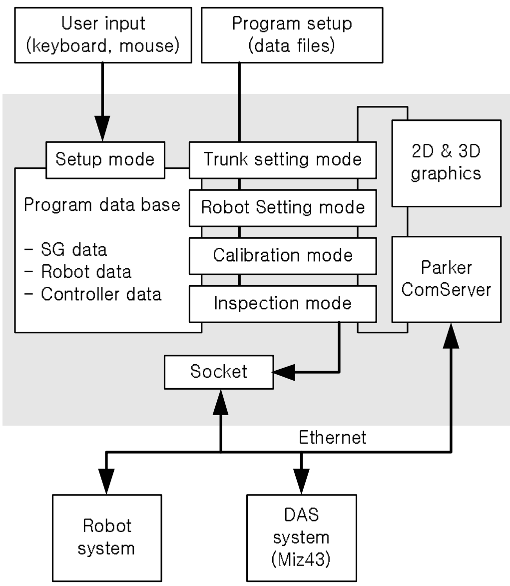

Fig. 9 Structure of the control program.

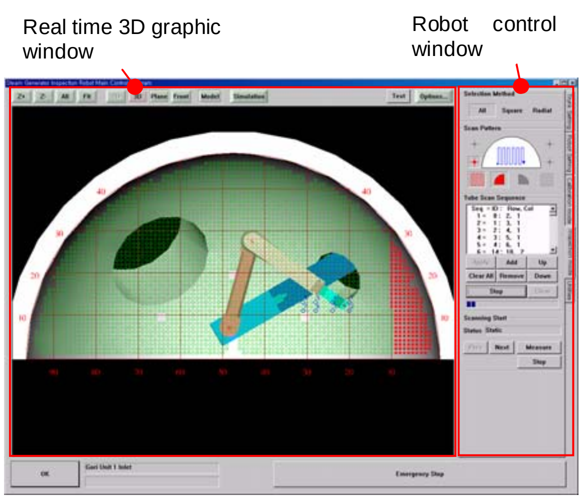

Fig. 10 GUI of the control program.

4. TOOLS AND DATA ACQUISITION SYSTEM

Eddy current test (ECT) which is one of the non-destructive tests is widely used to inspect for defects during the inspection of the SG tubes. The developed ECT probe insertion tool consists of a probe guide tube and camera head with LED illuminations. A multi probe insertion tool is also developed to reduce the inspection time. This tool is installed on the mast of the manipulator with dove tail V-blocks. Fig.11 shows a ECT probe insertion tools.

Cleaning the inside of a tube must be performed before tube maintenance such as plugging. Wire brushes and an electro-driving brushing tool are developed. Fig.12 shows a brushing tool and brushes.

A mechanic plugging tool is developed to be installed on

Fig. 11 ECT probe insertion tool.

Fig. 12 Brushing tool and wire brushes.

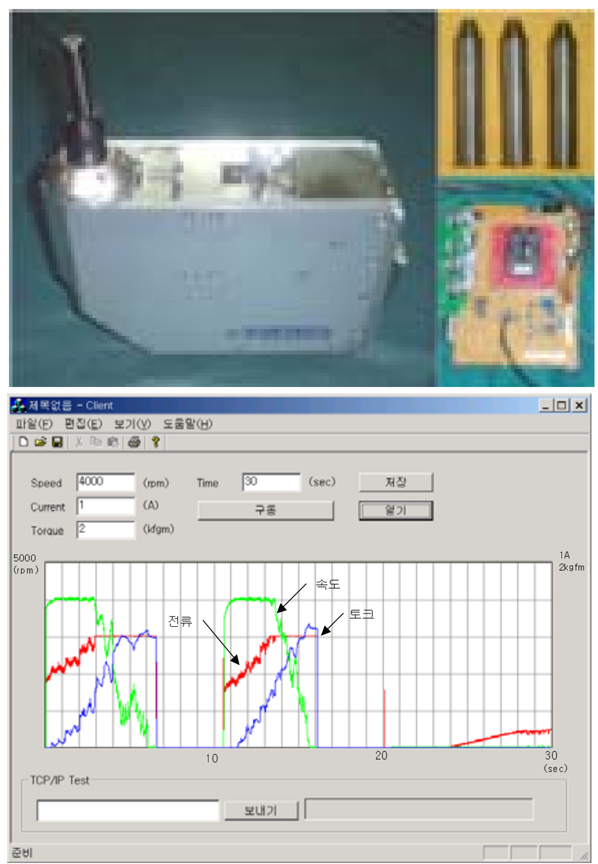

Fig. 13 Plugging tool system.

the mast. The plug expanding part is driven by a AC servo motor and has a self centered device when the part is inserted in a tube to uniformly expand a plug. Fig. 13 shows the plugging tool, sample plugs, control board, and the control program. The graph shows the control responses; the rotating velocity of the roller, current of the motor and the torque loaded on the plug.

A eddy current signal acquisition program is developed which can be run by a personal computer. The program communicates with a commercial data acquisition device (MIZ-43) through the Ethernet. Fig. 14 shows the data acquisition system and program.

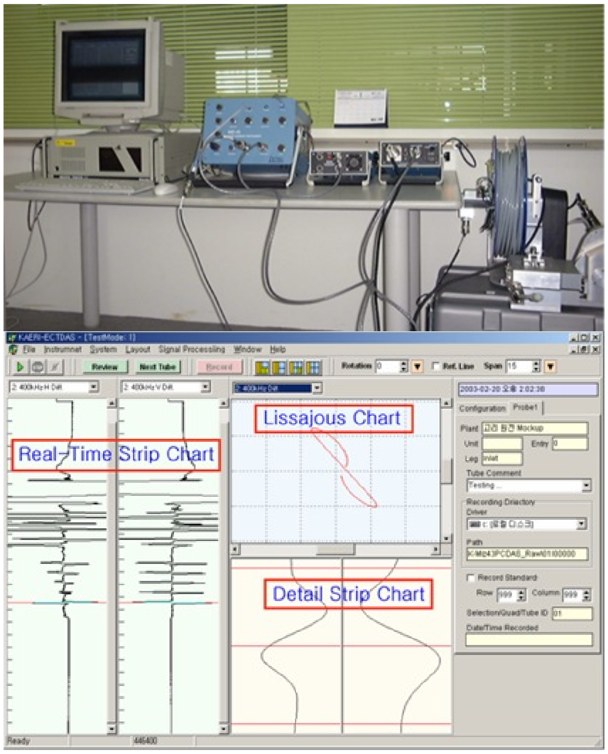

Fig. 14 Data acquisition system.

5. EXPERIMENTS

The developed robot system has been tested in the Ulchin NPP type steam generator mockup in a laboratory. The final function test was carried out at the Kori Npp type steam

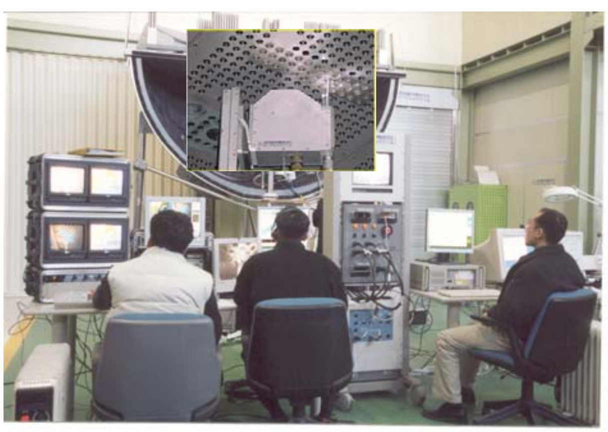

Fig. 15 The robot system test in Ulchin type SG mockup

generator mockup in the Kori training center. It takes 30 minutes for two workers to install the robot system onto the SG manway. Two workers communicate with a operator in the control room through the Audio/Video system. Fig. 15 shows the robot system test in the Ulchin type SG mockup. Status in the water chamber, probe push puller and tool head are shown on the monitoring system shown in the left side of Fig. 15.

6. CONCLUSIONS

A nuclear steam generator tube inspection/maintenance robot system was developed. For easy carriage and installation, the robot system consists of three separable parts: a manipulator, a water-chamber entering and leaving device of the manipulator and a manipulator base pose adjusting device. A software program to control and manage the robotic system has been developed on the NT based OS to increase the usability. The control program provides a real time 3-D graphic function which offers remote reality. The PID gains were tuned systematically by the time-delay control algorithm. The kinematics' parameters were calibrated with the D-H and Hayati's kinematics' model. The developed robot system successfully performs the inspection/maintenance work in the Ulchin NPP type steam generator mockup.

ACKNOWLEDGMENTS

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