Development of a SG Tube Inspection/maintenance Robot

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1. Introduction

A radiation hardened robot system is developed which assists in an 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 a 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 a 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 acquisition 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.

An 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 of three separable parts: a manipulator, a water-chamber entering and leaving device of the manipulator and a manipulator base pose adjusting device.

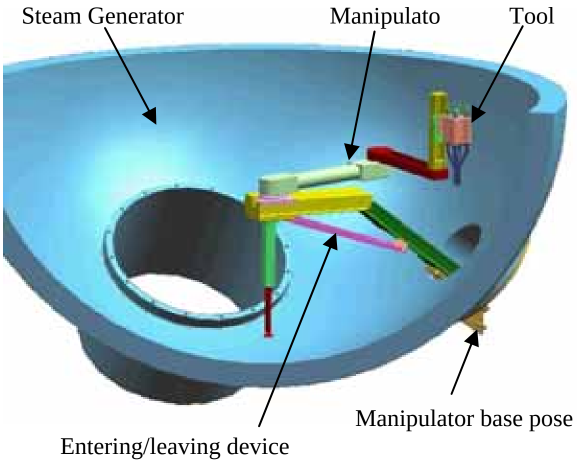

Fig.1. Steam generator heat exchanging tube inspection/maintenance robot.

2.2 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. 2 shows the remote robot control system.

Fig.2. Remote robot control system.

3. Position Control

3.1 Control Gain Tuning

PID gains of the motor drivers of the manipulator are tuned systematically with a time delay control (TDC) method [6]. Fig. 3 shows a block diagram of a PID control imbedded in the Tamagawa motor drivers.

The input torque of the motors is 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, $E(s) = L(e(t)), V(s) = L(\dot{e}(t)), v_d = 0$.

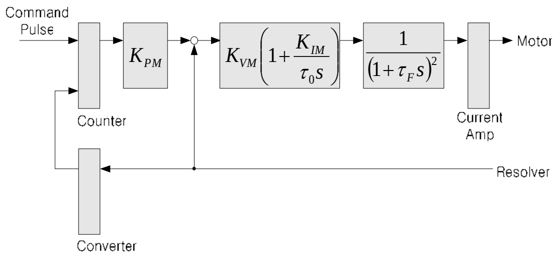

Fig.3. Block diagram of the PID control of the driver.

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

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

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

It is noted that the proposed gain tuning method is not only systematic but gives a better performance than a 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 the 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 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 the constants in the transformations vary by large amounts in that case [4]. To solve the problem, a modified Denavit-Hartenberg model proposed by Hayati and Mirmirani is used for the consecutive parallel axes [5].

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. 4.

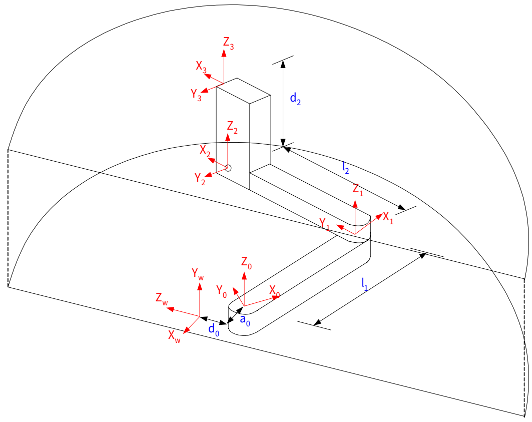

Fig.4. Coordinate frame assignment.

3. Conclusion

A nuclear steam generator tube inspection/ maintenance robot system was developed. For an 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 a 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.

Acknowledgement

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