Automatic Inspection of Reactor Vessel Welds using an Underwater Mobile Robot guided by a Laser Pointer

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Abstract: In the nuclear power plant, there are several cylindrical vessels such as reactor vessel, pressuriser and so on. The vessels are usually constructed by welding large rolled plates, forged sections or nozzle pipes together. In order to assure the integrity of the vessel, these welds should be periodically inspected using sensors such as ultrasonic transducer or visual cameras. This inspection is usually conducted under water to minimize exposure to the radioactively contaminated vessel walls. The inspections have been performed by using a conventional inspection machine with a big structural sturdy column, however, it is so huge and heavy that maintenance and handling of the machine are extremely difficult. It requires much effort to transport the system to the site and also requires continuous use of the utility's polar crane to move the manipulator into the building and then onto the vessel. Setup beside the vessel requires a large volume of work preparation area and several shifts to complete. In order to resolve these problems, we have developed an underwater mobile robot guided by the laser pointer, and performed a series of experiments both in the mockup and in the real reactor vessel. This paper introduces our robotic inspection system and the laser guidance of the mobile robot as well as the results of the functional test.

Keywords: underwater, mobile, robot, inspection, reactor

1. INTRODUCTION

The reactor pressure vessel is one of the most important pieces of equipment in nuclear power plants in view of its function and safety. The vessels are usually constructed by welding large rolled plates, forged sections or nozzle pipes together. In order to assure the integrity of the vessel, these welds should be periodically inspected using sensors such as ultrasonic transducers or visual cameras. Such inspections are usually conducted underwater to minimize exposure to the radioactively contaminated vessel walls.

The reactor pressure vessel in a pressurized water reactor has a cylindrical shape, and has inlet and outlet nozzles around the upper shell as shown in Fig. 1. It has many welds such as a circumferential seam, a weld of nozzle to the upper shell, a weld of flange to the upper shell and so on. When inspecting the welds of a vessel wall, the reactor head and the reactor internals are moved to the next canal so that the inspection can be performed efficiently. The reactor vessel is filled with water up to the top of the canal to reduce the radiation exposure during inspection. Thus, the inspection machine must be operated under water.

The reactor vessel inspection has been performed using a conventional inspection machine with a big structural sturdy column. This machine, however, is so huge and heavy that its maintenance and handling requires much effort to transport the system to a site and the continuous use of the utility's polar crane to move the manipulator into the building and then onto the vessel. Setup of this machine requires a large volume of area for work preparation and several shifts to complete.

In order to resolve these problems, we have developed an underwater mobile robot, which is guided by a laser pointer, and performed a series of experiments both in the mockup and in the real reactor vessel. The system is so small and compact that it will reduce the critical path process for pre-service inspection of pressurized water reactors. By deploying two robots simultaneously in the vessel, overall inspection time can be much reduced. This paper describes the outline of robotic

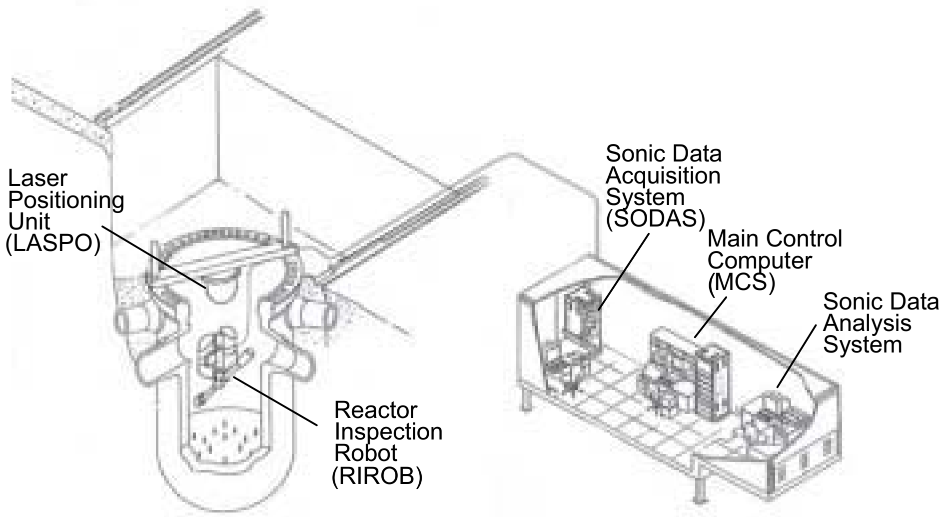

Fig.1 Configuration of the reactor inspection system (RISYS)

inspection system developed in our laboratory, and summarizes the experimental investigation and its results.

2. SYSTEM CONFIGURATION

The Our reactor inspection system, called RISYS, consists of a reactor inspection robot (RIROB), laser pointer (LASPO), main control computer (MCS), sonic data acquisition/analysis system (SODAS) and so on.

Fig.2 Reactor Inspection Robot (RIROB)

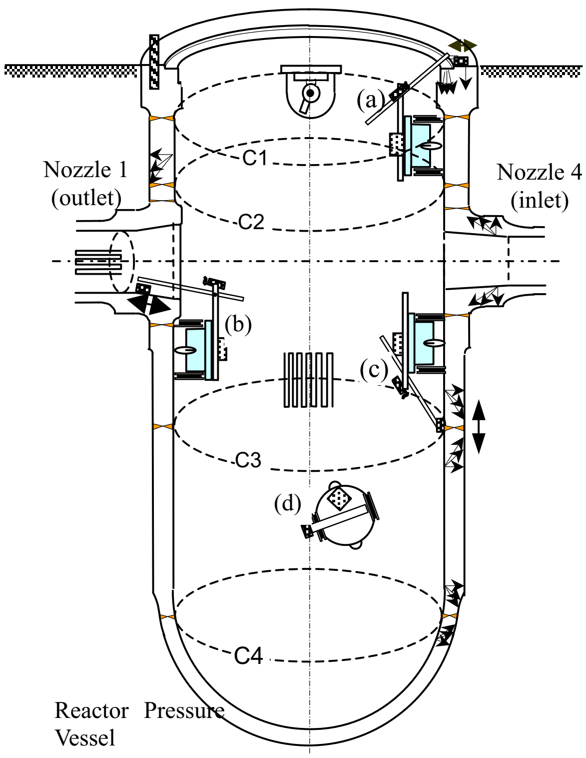

Fig. 3 Posture of inspection robot

Reactor Inspection Robot (RIROB) is a submarine type mobile robot whose weight is approximately 50 kg in air and becomes zero in water by the aid of floats. Most of the reactor pressure vessel in a PWR is composed of carbon steel and clothed inside with austenitic stainless steel. In order to climb the vertical wall of the vessel, RIROB has four magnetic wheels: two are caster wheels and the other two are driven by DC servo motors so that the robot can move in any direction on the vertical inner wall of the reactor vessel. The robot can control its linear velocity and angular velocity by the sum and difference of the velocities of the left and right driving wheels. Both the front and rear caster wheel are mounted on the parallelogram links with the robot body plate, so that the robot body can always be parallel to the wall, even though the wall is cylindrical.

The robot has also a light and long manipulator, and the ultrasonic probes are attached to its end effector. The manipulator has five degrees of freedom which are translation, twist, rotation, 4 consecutive translations, and probe rotation, as shown in the center of Fig. 2. The manipulator can reach up to 120 cm using 4 consecutive translation links.

The camera and lamp are mounted on the robot and the visual image from the camera is transmitted to the main control station. The robot has an inclinometer to measure the inclination of the mobile robot and to control the robot posture. The depth sensor is also mounted on the robot body to measure the water pressure and to calculate the current vertical depth of the robot.

Conventional inspection machine with huge manipulator can easily place its end effector equipped with ultrasonic probe to the desired weld position. However, the inspection system using an underwater mobile robot guided by a laser pointer, it needs much calculations and geometric analysis. In order to inspect the welds accurately, the robot should move exactly to the given position.

The laser pointer (LASPO) induces the robot to the next position. The laser pointer (LAPOS) is fixed in the middle of the crossbeam across the reactor upper flange. The laser pointer emits the laser beam to the next position for the robot to move. The robot, with the position sensitive detector (PSD) on its back, detects the deviation of the laser beam spot from the center of the position sensitive detector, and moves in the appropriate direction to make this deviation zero. The laser pointer is a kind of pan-tilt device on which the diode laser is mounted. The device is accurately driven by the micro stepping motors of which the resolution is less than 0.01 deg/step.

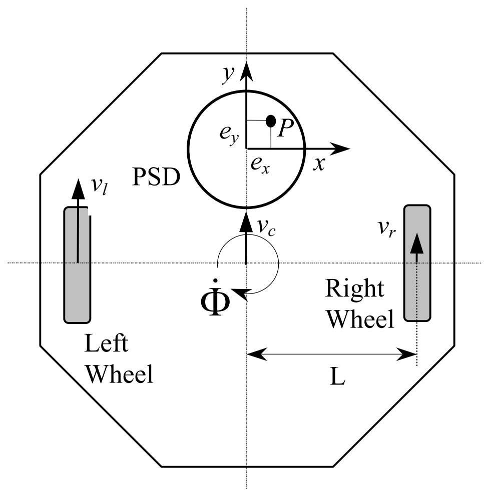

Fig. **4** Top view of RIROB with Position sensitive detector

Because the robot's position and direction are determined by the sum and difference of the velocities of the left and right wheel, which are driven by two DC servo motors, respectively. As shown in Fig. 3, the position sensitive detector (PSD) is mounted on the RIROB body plate. When the laser beam points to a position P on the PSD surface, the sensor generates currents corresponding to the deviation (e_x, e_y) of the laser spot with respect to the center of the PSD. We control the robot in such a way that

$$e_x = 0, \ e_y = 0 \quad (1)$$

More complex calculations are needed to inspect the welds near a nozzle using a mobile robot than the other welds in a reactor vessel. When inspecting the welds around a nozzle, the robot moves around this nozzle.

The function of the main control computer is to control RIROB, the laser pointer and the sonic data acquisition subsystem. It is PC based control station with operating software and interfaces. It has the geometric information of all reactor vessels operating in Korea, so that inspections can be planned and simulated on a 3D graphic display.

During inspection, the main control system generates the scan path for RIROB to move. Simultaneously, the current posture of the robot is displayed graphically and the image captured by the camera on the robot is also displayed. After inspection, examination reports are generated using the stored data. The system can also be operated in manual mode during computer control malfunction.

The computer software includes other convenient modules: input module of reactor specification, inspection procedures module, selection of inspection item, automatic finding of the inspection robot, previous simulation of robot movements, display of inspection status, communication with RIROB, LASPO and SODAS, fully automatic inspection and manual inspection, and so on.

The data acquisition subsystem drives the ultrasonic sensor, and collects, displays and stores the reflected signal data.

3. EXPERIMENTS

3.1 Experimental Overview

In order to confirm the integrity of our developed inspection system, we have performed a series of experiments in the reactor vessel mockup as well as in the real reactor vessel at Ulchine nuclear power plant in Korea. As shown in Fig. 7, the reactor vessel mockup is in the shape of a cylinder, whose dimensions are 5 meters high, and 4 meters in diameter. Prior to the underwater experiments, we had performed the experiment in air to confirm our laser guidance control method.

In this section, we describe underwater experiments of laser guidance around the nozzles, because here the guidance of the robot is most complex. Positioning accuracy is also examined, including the rotation and inclination accuracy of the underwater mobile robot, scan path accuracy of the manipulator, angle measurement accuracy of the pan-tilt unit of the laser pointer, and overall positioning accuracy of this system. The above results of functional tests indicate that the prototype inspection system satisfied most of the acceptance criteria.

The underwater experiments were usually performed using the following procedures:

1) move all equipment to the working floor of the reactor vessel mockup
2) mount the crossbeam with the laser pointer LAPOS to the stud bolts on the flange surface
3) move the robot RIROB underwater using a crane as shown in Fig. 7.
4) calibrate the position and orientation of LAPOS
5) perform a communication test with RIROB, LAPOS & MCS
6) check ready (self diagnosis)
7) guide RIROB to the start position using the laser pointer
8) execute the inspection: RIROB travel along the inspection path and the manipulator scans the welds (Fig. 9)
9) return RIROB to the home position
10) draw all equipment out of water and carry down to the control house

3.2 Inspection Procedures

In order to determine whether the weld has defects or not, we have conducted the well known ultrasonic testing. After emitting ultrasonic wave to the suspected welds, we monitor its reflected signal. Usually reactor pressure vessel is manufactured by welding several parts together. The welds to be inspected in the vessel is largely classified as (a) circumferential welds and (b) nozzle welds. Circumferential welds include the welds of flange to upper shell, upper shell to middle shell, middle shell to lower shell and lower shell to

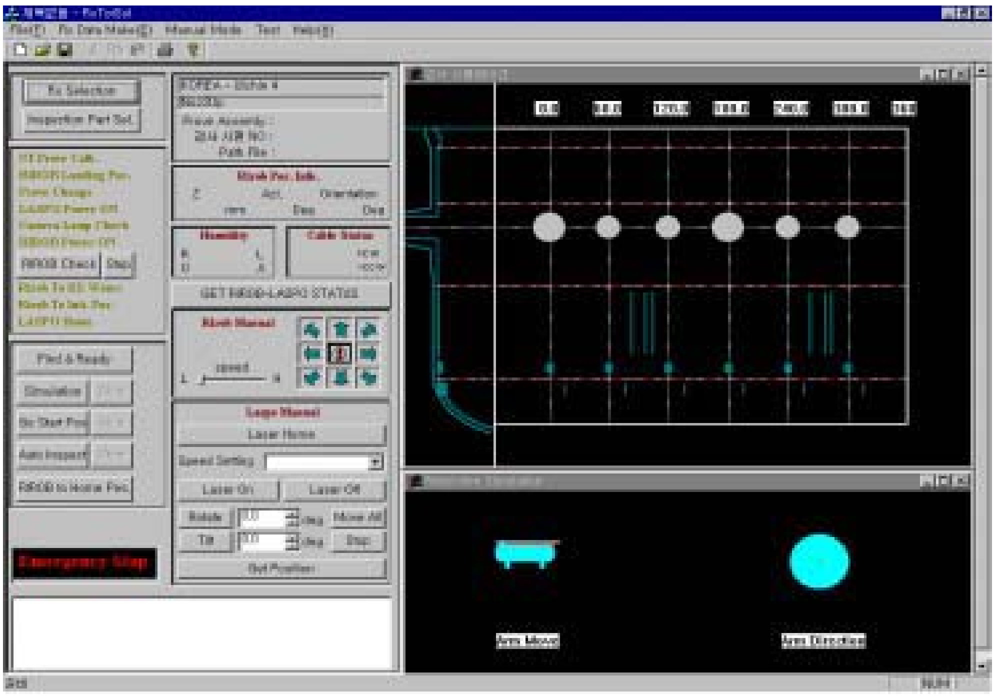

Fig. 5 Main display of the main control computer

bottom head, while nozzle welds include the welds of nozzle to middle shell, and nozzle to nozzle pipe so called safe end. Besides, flange ligament should be inspected. In some reactor vessel, vertical welds of reactor shell and safety injection nozzle welds are included in inspection item. Fig. 5 shows the location of the reactor vessel welds and the posture of the inspection robot (RIROB) for inspecting each welds effectively.

When inspecting each weld, we have to use various incident angles of ultrasonic wave for more accurate and strict inspection. For example, in case of reactor shell welds inspection, we use incident angles of 0, 45, 60, 50/70 degrees, respectively. In addition, for each incident angle, we have to scan the welds in four directions: upward, downward, clockwise and counter clockwise direction by using a ultrasonic probes with specified incident angle. Thus we have to inspect the welds seventy seven times in total.

Korean standard reactor vessel has six nozzles, thus the number of nozzle inspection becomes sixty times, and the number of circumferential weld inspection becomes sixteen times. The probe assembly should be cleverly designed to contact the probe plate to the weld surfaces with suitable compliance. Fig. 6 shows an example of probe assembly we use for reactor shell inspection.

Fig. 6 Experimental facilities

Fig. 7 Launching of the inspection robot

3.3 **Experimental Results and Improvements**

The objective of these experiments was to check if the system satisfied the given inspection criteria concerning position accuracy and repeatability of the robot movements. The criteria is that the ultrasonic transducer attached to the end gripper of the robot manipulator can be located to the desired position within an accuracy of 3 mm. This accuracy is determined by the accumulation of position errors from the laser pointer, robot

Fig. 8 Inspection of nozzle welds

Fig. 9 Scanning of nozzle inner wall

Fig. 10 Experiments in real reactor vessel

and manipulator. Each position error is measured and then the total error is also measured.

In addition, we experimented the extraction method of RIROB from the reactor vessel when malfunctioning and prepared a special procedure to deal with emergency situations. Through the functional tests, we confirmed that our robotic system met the given conditions, yet still requires many improvements. Such improvements include:
1) convenience of maintenance when assembling and disassembling
2) rigidness of the robot frame and manipulator
3) materials of the magnets of caster wheel and wheel shoe (urethane)
4) handling convenience with a hand grip of RIROB and cable handler of LAPOS
5) total reflection of the laser sensitive detector underwater
6) accuracy of the robot manipulator by reducing the compliance of the joints
7) sealing with a mechanical seal and monitoring leaks under operation
8) robot controller with dual CPU with DSP to increase the processing speed
9) optimum capacity of floats with cylindrical type

As a result, we designed a new system in consideration of the above necessary improvements, and are now carrying out the final tests for commercializing.

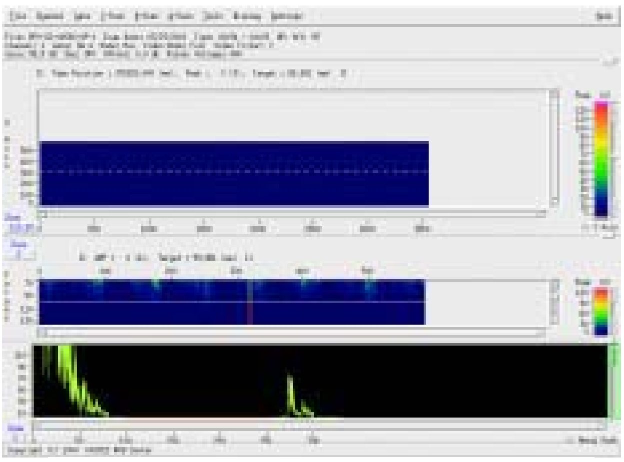

Fig. 11 Result of inspection (Display of C-scan)

4. SUMMARY

In order to improve the reactor vessel inspection system, we have developed a new robotic inspection system. We completed the laser induced control of the mobile robot, and the method is thought to be applicable to other industries. When our system is used practically for reactor vessel inspection instead of conventional machines, a lot of benefits are expected to result, such as in critical path process reduction and handling safety improvement, examination reliability and positioning accuracy, and so on.

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