Tele-Operated Mobile Robot for Visual Inspection of a Reactor Head

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Abstract: The control rod drive mechanisms in a reactor head are arranged too narrow for a human worker to approach. Moreover, the working environment is in high radiation area. In order to inspect defections in the surfaces of the reactor head and welding parts, a visual inspection device that can approach such a narrow and high radiation area is required. This paper introduces a tele-operated mobile robot for visual inspection of a reactor head, which has pan/tilt camera, fixed rear camera, ultrasonic collision detection system, and so on. Moreover, the host controller and digital video logging system are developed and integrated control software is also developed. The robot is operated by a wireless control, which gives flexibility for the inspection.

Keywords: tele-operation, reactor head inspection, remote control

1. INTRODUCTION

The Control Rod Drive (CRD) Nozzles for PWR (Pressurized Water Reactor) nuclear power plants entering the head of the Reactor Pressure Vessel (RPV) are specially designed container that houses the reactor core and the CRD Mechanism (CRDM) that regulate the power output of the reactor. In 2002, CRD nozzle leaks are discovered in several US plants and the defection of the RPV head is observed in a plant, which raises need to inspection of the RPV head. The primary method for detecting leaks from the CRD head penetration nozzle is to perform a visual examination of the nozzle to head intersection from the top of the head. Any areas that exhibit characteristic "white deposits" are indicative of boron salt residue coming from a primary coolant leak. However, the CRDMs in the reactor head are arranged too narrow for a human worker to approach. Moreover, the working environment is in high radiation area. In order to inspect defections in the surface of the reactor head and welding parts, a visual inspection device that can approach such a narrow and high radiation area is required. This inspections should be performed without removing the insulation which is a time consuming work.

Jamko Inc. [1] provided complete bare head visual examination and cleaning service for reactor head inspection in Southern California Edison (SCE) utility. R. Brooks Associates, Inc. [2] developed Brooks Top of Reactor Head Inspection System (BTRIS) and deployed it to North Anna 1 and 2, Farley 2, etc. Framatom ANP [3] also developed a bare-head crawler for the inspection. The lower part of the reactor head has been inspected by using a robot manipulator that is developed by KPS [4], [5], [6], [7].

This paper introduces a tele-operated mobile robot for visual inspection of a reactor head. The robot is installed to the RPV head by a human worker using a long stick with the robot attached in one end, which minimizes the personnel dose. Once the robot is installed on the head surface, the robot can be controlled remotely.

The robot can move between CRDMs and attached to the RPV head surface by using a magnetic wheel which prevent the robot from skidding down. Four ultra-sonic sensors are attached at each corner of the robot for detecting the displacement among CRDMs and robot for preventing from collision. A High quality small pan/tilt video camera is attached at front side of the robot for visual inspection and a body fixed camera is at the rear side for observing the rear side when retrieving the robot.

The remote controller is consist of a host controller, digital video recorder (DVR), LCD monitor, and a joystick controller. The host controller is a Pentinum PC with control software embedding the visual images and control buttons. The video images are carefully annotated to permit traceability and assurance that all nozzles have been examined. A mockup of a reactor head is manufactured with 12 CRDMs and the robot is tested on the mockup.

2. SYSTEM CONFIGURATION

2.1. Mechanisms

Figure 1 shows a schematic of reactor vessel. As seen in the figure, RPV head is shaped like a half sphere and the CRD nozzles are penetrated the head and heat insulation. The CRDMs are within the CRD nozzle. The number of CRDMs are from the mid-30's to over 100 in each reactor head. Each nozzle is approximately 4 to 5 inches outer diameter with a 0.5 to 1.0-inch (13 to 25.4-mm) wall thickness. The gap between the insulation and the top of the RPV head is at least 2-inch (50-mm) and the angle between the point at the lowest CRDM and the horizontal surface is about 50 *deg*, which means that the robot should be able to climb a slope angle more than 50 *deg* to access all of the CRDMs. Although there are numerous design differences among the various plants, the basic design and fabrication approach is similar.

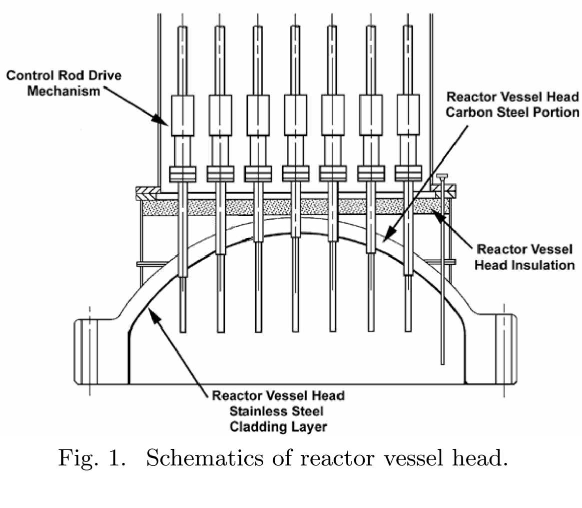

Fig. 1. Schematics of reactor vessel head.

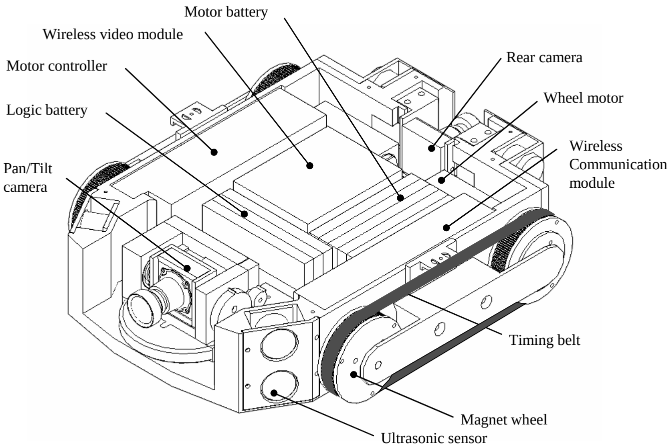

Fig. 2. A Schematic of the RPV head visual inspection robot.

Figure 2 shows a schematic of the RPV head visual inspection robot. Since the RPV head is not a plat surface, the robot can be skid down when the robot moves the lower part of the CRDMs. Moreover, it would be better for the robot to be stay in a certain position though the power is down unexpectedly. Therefore, an attachment mechanism is adopted by using permanent magnets. When permanent magnets are attached beneath the robot body to get the attachment force, the air gap can be varied according to the surface condition. Which results in unstable movement and requires many permanent magnets for getting enough attachment force. When permanent magnet wheels are used, there are not much flexibility for designing the mechanism because the manufacturing of the magnet is not as simple as steel. In this paper, the front wheels are made of a ring-shaped permanent magnetic wheel with both side attached by wheels made from steel. Since the contact between the head surface and the wheel is maintained while the wheel rotates, the attachment force is large and always constant with the assumption that the contact is maintained. Here, only the front wheels are constructed as a magnetic wheel because if all of the wheels are constructed by the magnetic wheel, the friction force is too large to steering the robot, which requires high current and consumes battery power too much.

The rear wheels are drived by dc motors manufactured by the Minimotor. co. ltd., the model number is 1717 with reduction gear and encoder. Since the reactor head surface is not flat, if the driving wheel is not contacted at the surface, the robot may not be move further. Therefore, each side of the front and rear wheels is connected by a timing belt to transfer the driving force to both the front and rear wheel.

2.2. Controllers

The robot has two drive motors for robot body movement and two motors for camera pan/tilt motion. The main controller is AT89C55 which is compatible with 8051 series microcontroller and is manufactured by the Atmel co. ltd. The main controller controls the drive and pan/tilt motors, gets the ultrasonic sensor signals, switches the cameras and light on/off, and so on.

Since the computational requirement for controlling four servo motors is relatively large, the servo control of the drive motor is separated from the main controller, that is, the drive motors are controlled by LM629, a single chip dedicated motion control processors designed for use with a variety of DC and brushless DC servo motors, which provides a quadrature incremental position feedback signal and an 8-bit PWM output for directly driving H-bridge switches. The control command is transferred from the main microcontroller.

The pan/tilt motor is controlled directly by AT89C55 microcontroller. The timer module within the microcontroller is used to generate the PWM control signal. The position of the pan/tilt motion is measured by two potentiometers, which is converted to 8 bit digital signal by using a AD converter.

2.3. Measurement devices

The robot is equipped with a pan/tilt camera with light sources made by high brightness LEDs at the front side of the robot for visual inspection and travelling on the working area, and a fixed camera at the rear side of the robot for retrieval of the robot. The cameras are wide angle camera so that they can provide wide viewing angle to the robot operator.

Four ultrasonic sensors are attached at the four corners of the robot for detecting collision with CRDMs. These sensors have an excitation frequency, maximum detection range, and minimum detection range by 40 kHz, 3 m, and 3 cm, respectively, and has a model name 'SRF04' made by Devantech inc. The maximum resolution that can be obtained from 40 kHz frequency is about 0.8 cm. However, one or two pulses can be omitted according to external conditions, which causes a limitation on the resolution by 1.6 cm.

2.4. Communications

The robot is operated based on the commands from the robot operator which are transferred through wireless communica-

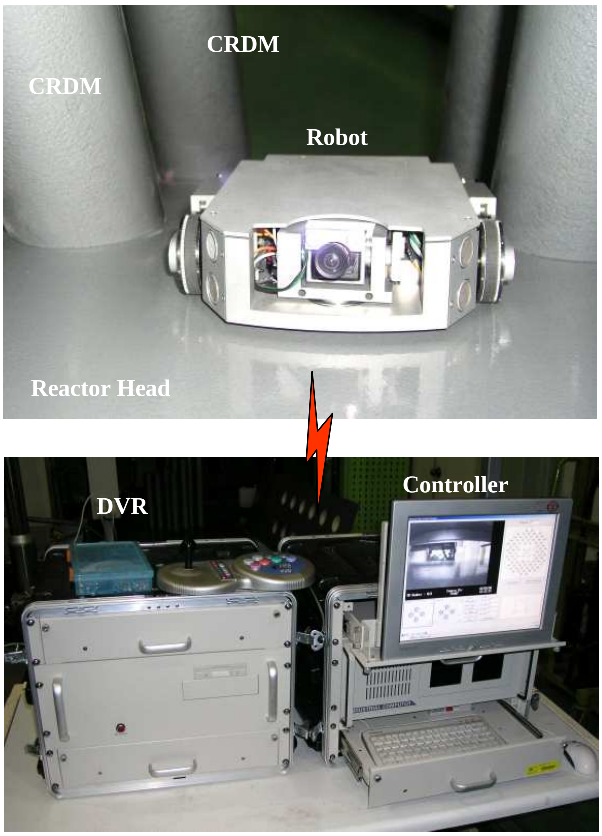

Fig. 3. Picture of the System.

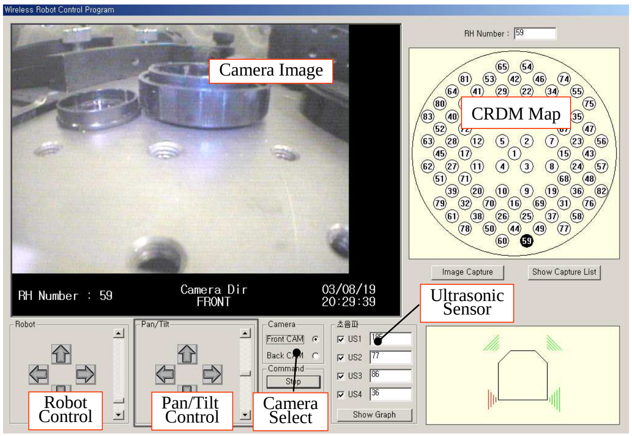

Fig. 4. Reactor head inspection robot control program.

tion with baudrate by 19,200 *bps* and RF carrier frequency by 900 MHz. The wireless module is manufactured by the MaxStream, co. ltd.
The video signal is also transferred through wireless communication with carrier frequency by 2.4 GHz and 1 W power which is sufficient for transmitting the video signal to the controller located outside of the RPV head. The carrier frequency of the data communication and the video transferring is different to avoid interference with each other. This wireless operation gives a freedom of the movement compared with a wired version of the robot whose movement is interfered by the cable.

2.5. Host control systems

A Pentinum 4 based industrial computer operated by Windows XP is used as the host controller. Joystick interface, wireless communication module, video switcher, and video capture board are included as the peripheral devices. A robot control program is developed for controlling the robot as shown in Fig. 4. The program has a graphical user interface (GUI) that has many button control to give commands to the robot for the robot movement control and pan/tilt motor control which can be done by using the joystick as well. The 'camera image' window displays the video image captured by the pan/tilt camera and rear camera which can be toggled by a button. The 'ultrasonic sensor' window shows the distance value measured from each corner of the robot to obstacles. These information is displayed as a graphical image in the right side of the windows as well. When an obstacle is closed to one of the ultrasonic sensor, the the color of the graphics in the corresponding side of the robot is changed from green to red, which helps the operator to travelling among CRDMs without collision. The 'CRDM Map' window shows the map of the inspected reactor head. When a CRDM is selected in the window, the identification number of the CRDM is displayed in the 'camera image' windows, which is recoded with the camera images by a digital video recorder (DVR) for future investigation. The DVR can store 16 video image simultaneously up to 40 GB.

3. Experiments

A simplified mockup of Korea Standard Reactor with 12 CRDMs is manufactured. The robot is attached to the mockup by a human worker and is controlled by using the host controller. The real time visual image displayed in the control window gives enough information to the robot operator when moving among the CRDMs. However, when the robot turns, the rear part of the robot can collide with a CRDM because the operator can not see the rear view enough only by using the fixed rear camera. In this case, When the rear part of the robot is closed to a CRDM, the graphic representing the ultrasonic sensor signal is changed to red, which gives warning to the robot operator. Then, the operator can change the direction easily.
Since the robot is operated by wireless remote control, the robot can move freely among the CRDMs, which not only reduces the inspection time but also makes multiple inspection possible. Here, multiple inspection means that several inspection robot can be installed simultaneously and perform the inspection without interfere each other.
When the robot is in the reactor head, there is no specific references to distinguish each CRDM. Which gives confusion to the robot operator. In order to provide easy control of the robot, automatic obstacle avoidance, navigation are needed for future research. The ultrasonic sensor signal can be used for developing a positioning system.

4. Conclusion

A tele-operated mobile robot for visual inspection of a reactor head was proposed. The mobile robot has pan/tilt camera for robot movement, rear camera for retrieval, ultrasonic sensors for collision detection, and high brightness LED lights. The robot is controlled by using wireless control which gives enough flexibility for the inspection and reduces the inspection time. Host controller and data logging system were developed. This control system can be used widely for controlling tele-robotic systems This robot is expected to replace a human worker working in a hazardous environment.

Acknowledgement

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