A Mobile Robot for Nuclear Power Plant Applications

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Abstract: Tele-operation and remote monitoring techniques are essential and important technologies for performing the inspection and repair tasks effectively in nuclear power plants. This paper presents the application of a mobile robot for the remote monitoring and inspection of the Calandria faces, where human access is limited because of the high-level radioactive environments during full power operation. The mobile robot was designed with reconfigurable crawler type of wheels attached on the front and rear side in order to pass through the ditch. The extendable mast, mounted on the mobile robot, can be extended up to 8 m vertically. This robot was also equipped a visible CCD/thermal infrared inspection head module and a stereo camera module for the enhancement of visual inspection.

Keywords: mobile robot, inspection, Calandria, crawler arm, extendable mast

1. INTRODUCTION

Robot applications are being expanded into the non industrial fields such as space, deep underwater, and high radiation areas. The robot plays the roll of a human worker in such areas since human access is extremely limited[1]. Nuclear robots, the first generation robots among the non-manufacture robots, are still expected in broad applications in nuclear facilities[2]. However, radiation exposure, high temperature, confined workspace, and a difficult approach to the work area are large hindrances in utilizing the robot for nuclear applications.

The applications of the mobile robot such as surveillance, inspection, and predictive maintenance are significant in order to increase the safety of nuclear power plants and decrease the radiation expose rate fundamentally considering the weight of nuclear power among the domestic total power product.

Calandria in a PHWR(pressurized heavy water reactor) nuclear power plant corresponds to reactor in PWR (pressurized water reactor) nuclear power plant. Nuclear fuels located inside the Calandria pressure tubes have to be exchanged regularly during normal operation. While the nuclear fuel is exchanged, an unexpected accident such as heavy water leakage causes large difficulties for power plant operation. Therefore, monitoring of the Calandria and a rapid identification of an accident situation is required to prevent a power plant trip and improve the safety and efficiency of the power plant operation.

For this purpose, KAERI(Korea Atomic Energy Research Institute) has developed a mobile robot system. The CCD/thermal infrared inspection head module and stereo camera module has been developed for this robot.

This paper describes the development of a tele-operated mobile robot, for the remote inspection of the Calandria face of the PHWR nuclear power plant during full power plant operation. The mechanical design, control system and an approach to enhance the inspection performances through the technique of superimposing a thermal infrared image into a real CCD image are also presented.

2. DESIGN OF MOBILE ROBOT

2.1 The work environments of Calandria face area

Fig. 1 shows the schematic layout of the vessel of the PHWR Nuclear power plants.

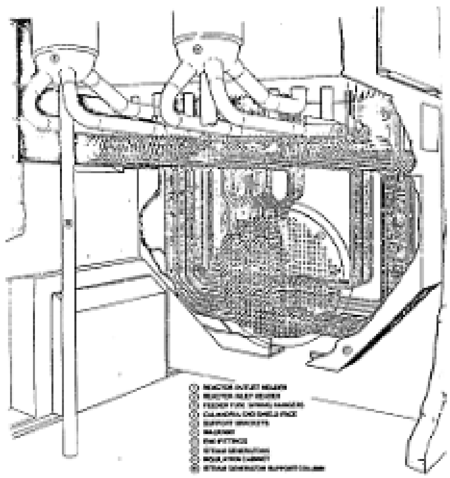

Fig. 1 Schematic layout of PHWR nuclear power plant

The diameter of the Calandria is about 7.6m. The 380 pressure tubes, filled with the nuclear fuel and heavy water, are passed through the Calandria of PHWR nuclear power plant horizontally. The temperature of the inside of the pressure tube is about 300 ºC. The pressure tubes are connected to the steam generator through the feeder pipes. The heavy water in the pressure tube is circulated through the feeder pipes which are connected to the pressure tube end fitting.

Nuclear fuels located inside of the Calandria pressure tubes have to be exchanged regularly during normal operation distinctive from the PWR. When the nuclear fuel exchange task is not carried out successfully or an unexpected accident such as heavy water leakage occurs, rapid identification of an accident situation is really important from the viewpoint of power plant safety and effectiveness. Unfortunately preventive maintenance work during normal operation and nuclear fuel exchange involves complex tasks and the environment is inherently hazardous because of high radiation and contamination. Therefore a highly robotized system must be used to carry out such hazardous tasks instead of human operators for the Calandria face inspection.

2.2 Design Criteria for Mobile Robot

There are several severe constraints for a mobile robot in approaching the Calandria face area and performing the inspection tasks. It should be satisfied with the following constraints in order to navigate inside the nuclear power plant vessel and inspect the Calandria face.

- Robot has to pass over the service area gate to approach the Calandria face area. The dimension of the gate is 2 m height and 1.5 m width. Hence this dimension is the permitted maximum value of the mobile robot.
- Radiation shelter is located between the service area and Calandria face area. There is a ditch of a width of 0.75 m below the shelter for the opening and shutting of the shelter. The mobile robot can traverse this ditch without any restriction
- Extendable mast mounted inspection module can move up and down to the maximum height of the Calandria for the effective inspection

Besides the above mechanical constraints, misbehaviors due to radiation exposure should be avoided in the evaluation of the radiation effects of its electric and mechanical components for use in the high radiation level of the Calandria face environment. The mechanical components such as motors, bearings, oil and O-ring should be selected with consideration of the radiation effects. Similarly radiation weak electric components should be exchanged for radiation hardened components or made radiation resistive

2.3 Mobile Platform

The Mobile robot should be able to traverse the ditch of a width of 75 cm and depth of 25 cm for the radiation shelter wall guide rail in order to have access to the Calandria face area. To fit this constraint, a specially designed four wheeled structure with a reconfigurable crawler arm was adopted as a mobile mechanism.

The reconfigurable crawler arm was attached to the front and rear side of the four wheeled mobile system in order that the robot can pass over the ditch safely. The distance between the front wheel and rear wheel was 48 cm with consideration of the dimension of the wheel, and the length of the crawler arm was determined as 53.5 cm for the passage of the guide rail ditch. The front wheels located at the side mobile platform were connected to the rear wheel through the chain.

The crawler arms were actuated through the double axis inside the wheel actuation assembly. Table 1 shows the major specifications of the mobile platform and Fig. 2 shows the procedure for the ditch passage of the designed mobile of robot.

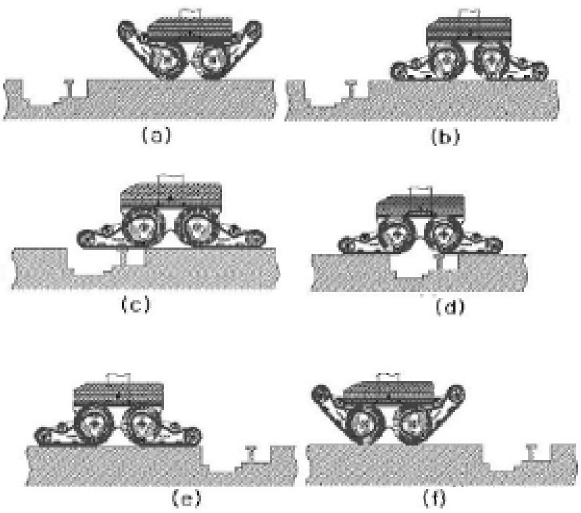

Fig. 2 Procedure for the guide rail ditch passage

Table 1 Major specifications of mobile platform

Items	Specification
Height	400 mm
Weight	90 Kg
Distance of wheels	480 mm
Length(full stretch)	1550 mm

2.4 Extendable mast

The extendable mast, mounted on the center of the mobile platform can move the head mounted inspection device along the vertical direction.

It requires a maximum reachable height of 8 m when it is fully stretched out. And It should be able to shrink below the height of 2 m for the passage of service area shelter door. The volume of the mast is also restricted since the extendable mast should be mounted onto the mobile platform. Also, its weights should be minimized in order to maintain a stable robot posture during inspection tasks. There are various types of the extendable masts commercially available. But the maximum reachable height of commercial mast is below 4 m. And it requires auxiliary devices such as a hydraulic pump, air compressor, or steel band. Therefore, the direct use of the commercial one won't fit for the robot because of their large volume and reachable height.

We designed a multi link type extendable mast using a spiral screw in order to overcome the above-mentioned constraints. Fig. 3 shows the inner structure of extendable mast and its components.


Fig. 3 Inner structure of the extendable mast

As the screw located at the inner center of the link rotates, the link begins to move. When the nut of the link is released from the screw, that link is locked with the prior link. Table 2 represents the major specifications of the designed extendable mast. Fig. 4 shows appearance of the developed robot.

Table 2 Major specifications of the extendable mast

Items	Specification
Length of link	550 mm
Number of link	16 ea
Minimum height	1.2 m
Maximum height	8.0 m
Weight	29Kg

Fig. 4 Appearance of the developed robot

3. INSPECTION DEVICE

3.1 Stereo Camera Module

A stereo imaging system is widely used in the tele-operation and inspection of working areas where the human operator's approach is limited, and in the structure analysis of the material to enhance the observer's visual understanding. Especially for tele-operation of the severe working environment such as deep sea, space, high radiation area, a stereo imaging system is indispensable and usage of this makes their working time short, and raises the efficiency of remote tasks to a higher degree.

A horizontal-moving axis stereo camera was developed and mounted onto the mobile robot. This stereo camera was based on the linear relationship between the vergence and focusing control[6]. Both the vergence and focusing were controlled simultaneously by regulating either the vergence or focusing. Fig. 5 shows the inner structure of the stereo camera and Fig. 6 shows the stereo camera mounted on the robot.

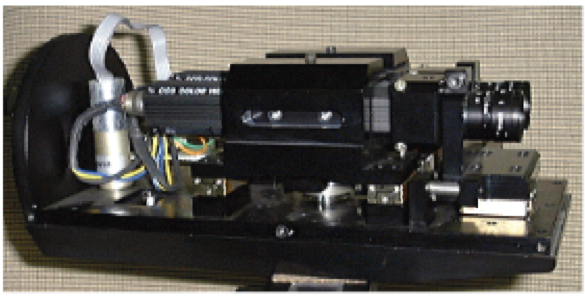

Fig. 5 Inner structure of stereo camera

3.2 Thermal infrared inspection head module

Defects such as cracks, inclusions, voids, or delaminations conduct heat at a rate different from that of the defect-free material. Thermal infrared imaging techniques are now used in monitoring the conditions of many kinds of engines, electrical and mechanical elements, and processes in a variety of industrial plants[7]. Many industrial plants use a thermal infrared imaging system carried on a mobile robot for this purpose.

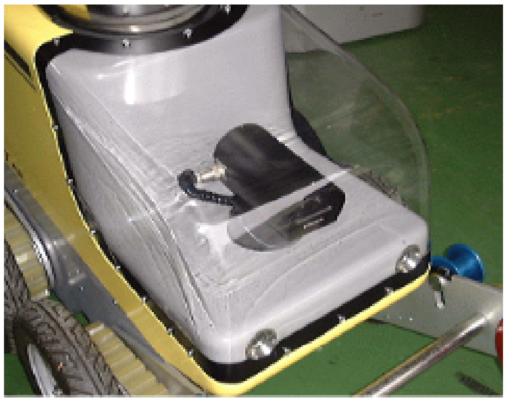

Fig. 6 Stereo camera mounted on the robot

We have developed the CCD/thermal infrared inspection head module for the mobile robot as the sensing mechanism, which we use in conjunction with the color CCD camera and a PV-320 thermal infrared camera.

The PV-320 is a commercially available low-cost thermal infrared camera. We used a commercial CCD camera since the dimension and the weight of the radiation hardened camera is not able to be attached to the extendible mast. We designed the inspection head module from the point of easy replacement. This scheme is more economic than using the radiation hardened camera.

Fig. 7 shows the shape of the thermal infrared inspection head module. Table 3 represents the major specifications of the thermal infrared camera.

Fig. 7 Thermal infrared inspection head module

The PV-320 thermal infrared camera and the CCD camera are placed in parallel. The narrower the horizontal distance between the thermal infrared camera and the CCD camera is, the larger the shared FOV in the horizontal direction.

The low-cost thermal infrared camera suffers from poor spatial resolution compared to the commercial CCD cameras. The thermal image monitoring program was developed to enhance the inspection performances for the Calandria of a nuclear power plant through the technique of superimposing a thermal infrared image into a real CCD image as shown Fig. 8.

Table 3 Major specifications of thermal infrared camera

Parameter	Specifications
FOV [HXV]	34.4 X 26.2°
Spectrum Range	2～14 ㎛
Detector	320 X 240 pixels Focal Plane Array
Array Size[H X V]	15.52 X 11.64mm
Field rate	60Hz
Focal Length	0.7m ～ ∞
Effective Cell Size	48.5 X 48.5㎛
Thermal Sensitivity	0.2℃@25℃
Weight	2.3kg
Lens	25㎜
Size [W X H X D]	140 X 114 X 114㎜

We utilized a Matrox Meteor-MC4 frame grabber board, for providing 4-video signal inputs, in an industrial PC rack-mount chassis, with a Pentium II processor card. The software platform was based on the Windows 98 operating system and consists of custom native libraries, MIL-LITE 6.1, for image capture, digitizing, memory transfer, and display. The Code was written in the MSVC6.0 programming language.

In the occurrence of thermal abnormalities at observation points and areas of the Calandria face area, an unusual hot image taken from the thermal infrared camera is mapped upon a real CCD image.

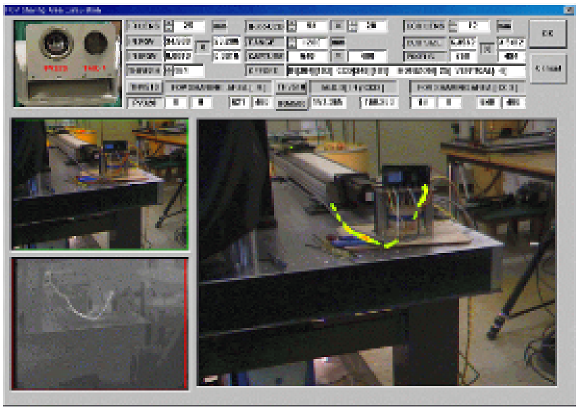

Fig. 8 Superimposing thermal image into real CCD image

4. CONTROL OF MOBILE ROBOT

4.1 Remote control part

The control system of the developed robot can be classified into the supervisory control part and the remote control part. Fig. 9 represents the control scheme of the robot.

The remote control part, located inside the robot, was composed of a 8051processor board, digital I/O board, and a camera control board. It takes the roll of a control for the inspection device control, such as stereo camera pan/tilt and focus, thermal infrared inspection head module focus and pan/tilt based on the commands transmitted from the supervisory control part. It also reads the incline sensor data of the robot body. The remote control part communicates with the supervisory control part through the RS-422 protocol.

The complex electronic components have more fault possibilities than simple passive components from the viewpoint of a radiation effect. We designed the remote control part with the above concepts. The thermal infrared camera module is controlled by the relay circuit.

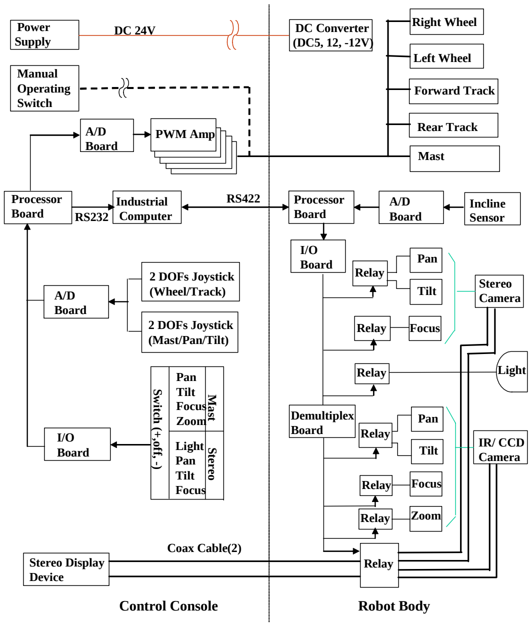

Fig. 9 Control scheme of robot

A radiation hardened 8051 processor was used for the remote control part. Also some radiation hardened components such as TTL, Memory IC were used. Electric components such as diode, A/D converter, OP amp, multiplex were selected among the commercial ones because of their radiation hardening characteristics.

4.2 Supervisory Control Part

The supervisory control part takes the roll of the human interface and wheel, crawler arm, and extendable mast control. Fig. 10 shows the supervisor control part. We utilized an industrial PC with a Pentium II processor card as a host computer. The software platform was based on the Windows 98 operating system and the control program was written in the MS VC6.0 programming language.

Fig. 10 Supervisory control part

4.2.1 Control Panel

The control panel shown in as Fig. 11 includes 2 joysticks and various buttons for the robot body operation, mast operation, and inspection device operation. The manual operation switches are prepared in this panel for an emergency.

A 8051 processor board, attached digital I/O board, and A/D board, are located inside the control panel box. This processor reads the switch and joystick value of the control panel and sends the command to the host computer through the RS232 port.

Fig. 11 Control panel

The robot wheel, crawler arm, and mast actuating drivers were mounted on the supervisory control console. This control scheme is unusual. But this configuration circumvents the radiation effect of drivers and makes maintenance easier. The control panel processor actuates these drivers without host computer intervention. And it informs the host computer simultaneously.

In the case of an unexpected malfunction of the robot during the inspection operation, the robot can be retrieved avoiding an influence to the power plants operation. The operator can retrieve the robot through the operation of a manual switch which is located at the control panel.

4.2.2 Stereo Display Device

The display types of the stereo image are classified into color separation, polarization, and electric shutter and HMD according to the transmission method of L, R images to human eyes.

Polarization type display device uses polarization principle in separation and transmission of left and right images. As shown in Fig. 12, the two images passing through the polarization panels in front of L, R monitors are combined by the semi-reflective mirror.

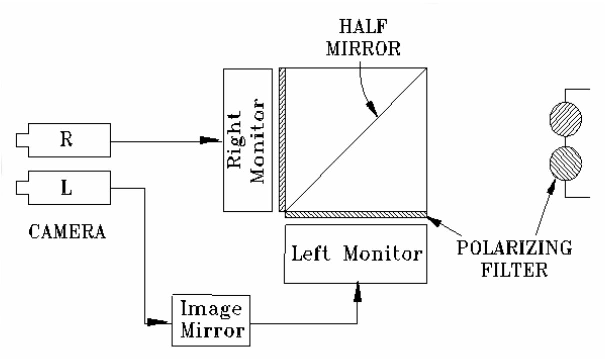

Fig. 12 Principle of Polarization type stereo display

Then observers can see the two L, R images separately by using polarization glasses. Each lens of the glasses has the same direction with each polarization panel, so each eye can see each input image of the camera.

In this paper we developed a polarization type light weighted stereo image display device with TFT-LCD monitors as shown Fig.13.

Although having a somewhat darkness due to the polarization filter, this polarization type gives higher resolution than the electric shutter type.

Fig.13 Polarization type stereo display with TFT-LCD

5. CONCLUSIONS

The Application of the mobile robot for the inspection of nuclear power plants is a significant project in order to increase the safety of nuclear power plants and decrease the radiation expose rate fundamentally considering the weight of nuclear power among the total domestic power products.

The development of a tele-operated mobile robot, for use in a highly radioactive environment of the Calandria face at the PHWR nuclear power plant has been described. The inspection performances of the mobile robot have been enhanced through the technique of superimposing a thermal infrared image into a real CCD image.

The significance of this development is to provide a robotic system that can be operated from remote locations to perform the given tasks during 100% power operation.

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