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DESIGN OF THE REACTOR VESSEL INSPECTION ROBOT FOR THE ADVANCED LIQUID METAL REACTOR*

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A consortium of four universities and Oak Ridge National Laboratory designed a prototype wall-crawling robot to perform weld inspection in an advanced nuclear reactor. The restrictions of the inspection environment presented major challenges to the team. These challenges were met in the prototype, which has been tested in a mock non-hostile environment and shown to perform as expected.

INTRODUCTION

The Center for Engineering Systems Advanced Research (CESAR), sponsored by the Department of Energy (DOE) Office of BAsic Energy Sciences, represents an engineering center with focus on intelligent machines. With support from the DOE Office of Nuclear Energy, CESAR has been performing applied robotics research, systems integration, and overall coordination and management of a consortium of four research groups at the universities of Florida, Michigan, Tennessee, and Texas, in a program of robotics for advanced nuclear power stations. The goal of the team is to develop a generation of advanced robotic systems capable of performing complex surveillance, maintenance, and repair tasks in nuclear energy facilities and other hazardous environments. The strategy to achieve these goals consists of utilizing and advancing state-of-the-art robotics technology through close interaction between the universities, national laboratories, commercial robot producers, and manufacturers and operators of nuclear power plants.

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During the past year, the team designed a wall-crawling robot for weld inspection on the Advanced Liquid Metal Reactor (ALMR) reactor and containment vessels, as well as in other modern power reactors. Design efforts for the reactor vessel inspection robot (RVIR), concentrated on the ALMR because it presents the most demanding environment in which the robot must operate. Reactor vessel weld inspection in the ALMR occurs during refueling outages, which present a 36-hour window for this task. The use of liquid sodium as the primary coolant presents several problems for weld inspection. First, the chamber around the reactor vessel is filled with argon, to preclude the adverse interaction between sodium and oxygen. This requires deploying the RVIR through a gas lock to preserve the environment around the reactor vessel. Second, the shutdown temperature must be maintained at about 204°C to keep the sodium in a molten state. Third, radiation levels start at a relatively high level, approximately 100 REM/hr., and taper as shutdown time increases. Fourth, there is an emissive coating on both the outside of the reactor vessel and the inside of the containment vessel which must be protected from damage by the robot as it performs its tasks. Finally, the space provided between the reactor vessel and the containment vessel (about 15-20 cm) is smaller than in other modern reactors, with an entry port about 13 by 38 cm. With these restrictions, designing to the requirements of the ALMR insures a robot that will perform in less demanding environments associated with, for example, the modular high temperature gas cooled reactor or the advanced light water reactors.

CHASSIS DESIGN

During conceptual design of the RVIR, the team considered a number of wall attachment and locomotion configurations, including vacuum-activated suction cups in a walker arrangement, magnetic attraction with motor-driven wheels and a spring-loaded wheeled design which would wedge the robot between the walls of the cavity in which it operates. The temperature and radiation levels dictated that as much of the electronics as possible be located off-board the robot and outside the immediate reactor vessel environment. Those electronics which must remain on-board, such as the three video cameras and the weld-inspection sensors, must be cooled and either radiation tolerant or shielded.

The proof-of-principle prototype RVIR consists of a chassis containing two sets of vacuum suction cups that can alternately grasp the side of the vessel being inspected. The RVIR chassis is shown in Figure 1 below. At the corners of the RVIR are four suction cups which can slide on channels inside the chassis to permit the robot to walk forward or backward. These cups and their associated channel slides are shown as items a in Figure 1. Linear translation of these corner cups is accomplished by an electric motor-driven worm gear (item b in Figure 1). This apparatus provides about 10 cm of translation. A second set of three suction cups is attached to a centrally-pivoted plate under the center of the RVIR chassis (Fig. 1, part c). This set of cups provides steering functions when the rotating servo device (Fig. 1, d) is actuated. Each set of suction cups can be extended to or retracted from the surface on which the robot is crawling. Extension and retraction of the sets of suction cups is accomplished by compressed gas cylinders (Fig. 1, f). When the sets are alternately extended and activated (vacuum applied), the RVIR's crawling or steering functions can be accomplished by either activating the linear translation system or rotating the turning servo device. Performing these individual steps in rapid sequence, under computer control, permits the robot to navigate around the surface of the vessel being inspected.

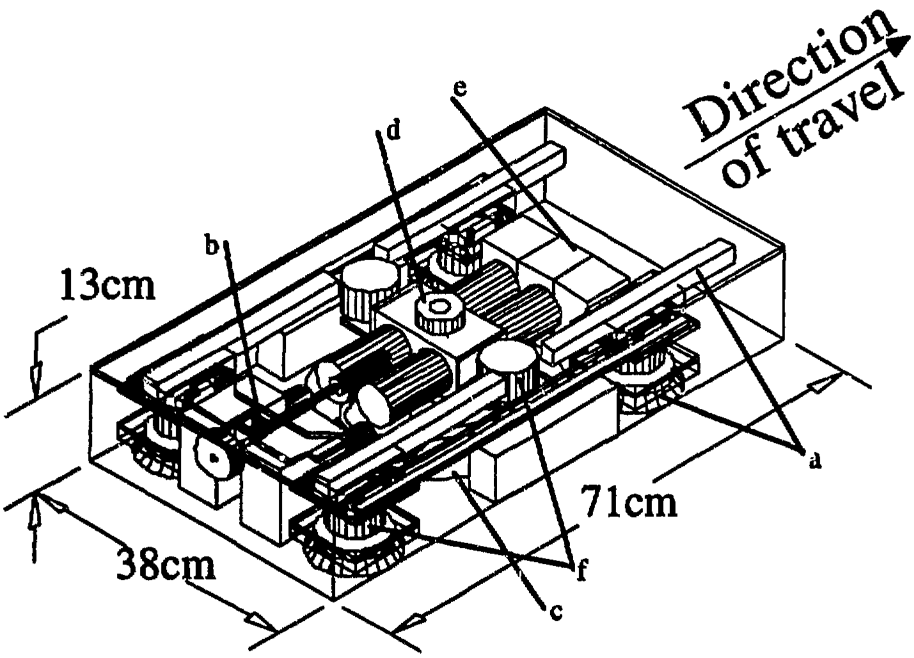

Figure. 1. RVIR cutaway diagram showing the linear (a) and rotary (c) suction cups, the steering servo (d) the suction cup extender servos (f), and the sensor box (e) toward the front.

This prototype robot was designed and built over a seven-month period which terminated with a demonstration of its walking capabilities on a curved aluminum wall designed to simulate the surface characteristics and geometry of the ALMR reactor vessel. All components in the RVIR meet both the temperature and radiation requirements, with the exception of the pneumatic servo valves and tether hose. These items can be obtained to meet the environmental requirements, but were not for the prototype primarily because of cost. Similarly, the compressed gas used to power the prototype was air, although the actual robot would run on compressed argon. All electronics are located off board due to the high heat in the robot's operating environment. The tether for the prototype consisted of a standard compressed air hose, and electric cabling to carry signals from the onboard sensors to the off-board control computers, and to carry action commands from these computers back to the RVIR. For an RVIR deployed in the reactor vessel environment, the tether would have the air hose replaced with an appropriate high-temperature/high-radiation hose to carry the compressed argon. In addition, there would be a steel cable for robot retrieval in case of failure, and a fiber-optic cable to carry video images from the RVIR sensor suite to the off-board vision-processing system.

CAMERA SYSTEM

The RVIR requires a vision system capable of permitting the robot to follow visually distinct welds along the surfaces of the two vessels. These weld seams on the ALMR vessels result from a grinding process which flattens the welds after the black emissive coating has been applied. Thus, the weld seams comprise a silver band within the black surround. A vision system capable of following and inspecting these welds was designed and tested in simulation. The size of the system is constrained by the size of the RVIR, which in turn is constrained by the working environment described above. The vision system consists of three small CCD cameras mounted in a sensor box, each camera being 4.6 cm (W) by 7.0 cm (H) by 2.7 cm (D). Each camera is equipped with a 380-line high-resolution, automatic iris, internal synchronization, automatic shutter and low lux (<2 to 100,000 lx) adjustable optics. Operating on low power, these cameras feature remote optical heads and six-element infrared LEDs. The output signal is standard NTSC, which can be sent to any VCR, monitor, or vision processing system.

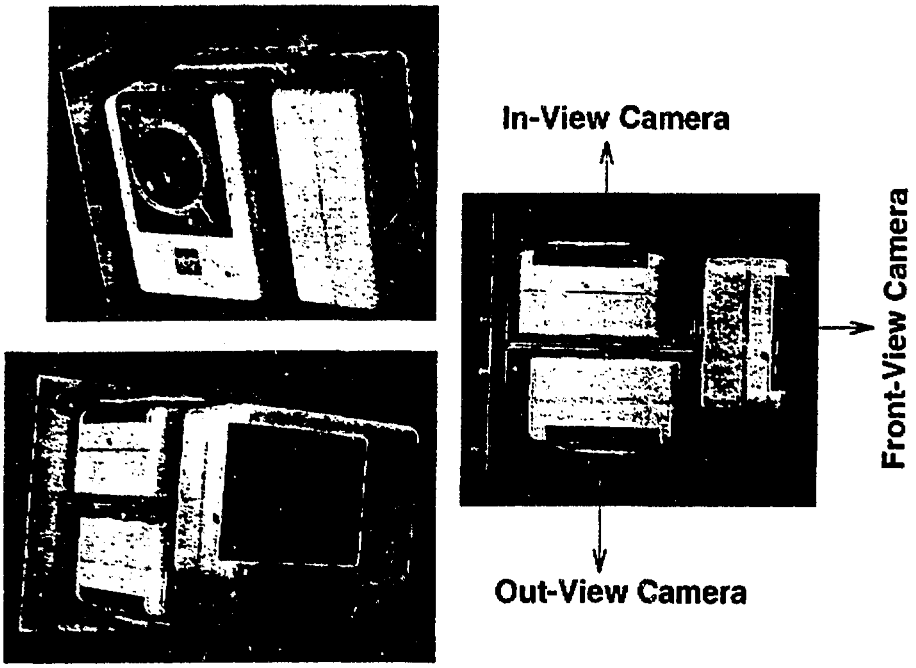

FIG. 2. Camera configuration of the RVIR vision system.

The simulation used to preview the images generated by the RVIR's cameras is based on a ray-tracing algorithm which helps determine the capabilities and limitations of the vision system. Several image sequences of numerical and Braille-code pattern weld markings were taken by the front-facing and the down-facing cameras. These patterns were used to help design the size and interval of the weld-marking patterns to make the inspection task easier to perform. The three-camera sensor module configuration, shown in Figure 2, fits into the sensor module which is labeled as item e in Figure 1. The forward-looking camera is oriented in the direction of RVIR travel, and the other two are oriented to the top (out-view camera) and bottom (in-view camera) of the RVIR..

SENSOR MODULE DESIGN AND TESTING

The high temperatures of the ALMR environment require that all robot components be able to tolerate such temperatures. Although some heat-resistant components exist, not all sensors have such robust characteristics, and when they are available, their prices tend to be considerably higher than the standard equipment. Hence, development of a capability to cool the critical equipment, such as the cameras, in hot environments is required for the RVIR.

For cooling the RVIR sensor module, three cooling system design alternatives were considered: Forced convection; air conditioning (AC), and vortex tube technology. Since forced convection is not effective in high temperatures, and AC is a relatively complicated design, employment of a vortex tube is the most suitable option. Vortex tubes (see Figure 3 below) are simple devices which convert compressed gas into two flows: one of hot air and one of cold air. A vortex tube operating with 100 cfm of compressed inlet gas at 6.9 X 10^5 Pa and 21°C can produce cold air at 10°C. Vortex tubes built by Vortec Co. have cooling capacities

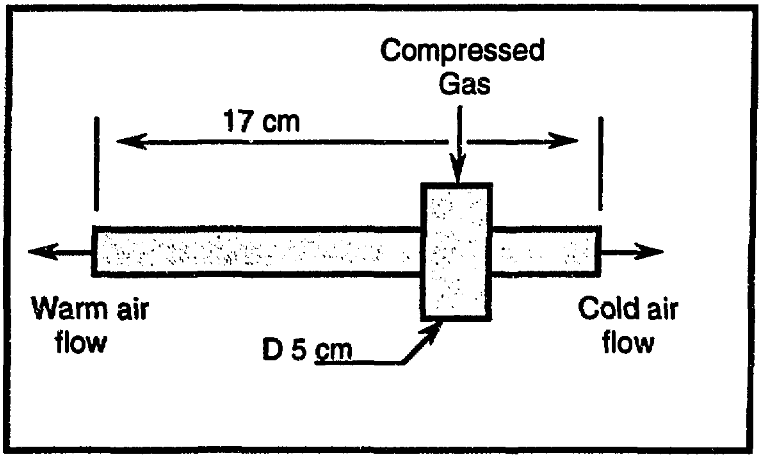

FIG. 3. Diagram of Vortex tube technology.

from 30 W to over 1700 W. Advantages of a vortex tube include simple design with no moving parts, operation only on compressed gas (no electricity is needed); easy adjustment of gas flow and temperature, and the ability to effectively cool an enclosed volume.

The prototype RVIR requires the enclosure only of the three CCD cameras. For this purpose, an enclosure design was developed which allows easy assembly and disassembly of the module for maintenance and sensor replacement purposes. Structurally, it contains two pieces: (1) Base frame with two sides; the CCD cameras and vortex tube are mounted on one side; the second side is used to attach the unit to the body of the robot, and (2) Cover shell with four sides, three of which contain windows for cameras. The module's outer shell is constructed from thin steel sheet, and insulated from the inside by two layers of aluminum paper which has excellent insulation properties. Outer dimensions of the module are approximately 10 x 13 x 13 cm . The unit weighs about 2kg including the three cameras, vortex tube and all attachments.

A laboratory testbed was developed to assess the performance of the sensor module at temperature. While the sensor box was heated in a furnace, its interior was cooled by a vortex tube (Model 208 by Vortec Co.). Thermocouples located inside and outside of the module recorded temperature readings. During the tests, when the outside ambient temperature was 211°C , module interior temperature remained at 14°C, which was satisfactory. To assess the effectiveness of the vortex tube's cooling capacity, a similar test was run without using the vortex tube. In this control test, only compressed air at 6.9×10^5 Pa was supplied to the sensor module. In this test, module interior temperature rose to 49°C in the first 12 minutes. Since the cameras can not operate above that temperature, the test was terminated. This test procedure demonstrated the effectiveness of vortex tubes in this application, and indicates that vortex tubes may be used successfully to cool sensitive electronic components enclosed in small volumes.

NAVIGATION

The navigation problem consists of two major parts: (1). Weld Tracking: The function of the robot is to inspect, the weld along the circumference of the reactor and containment vessels. This task requires the design of algorithms which generate steering commands to achieve weld following. (2). Fault Localization: Whenever a fault is detected on the weld, the robot must be able to report the location and orientation of the fault precisely.

Visual Weld Tracking: In the RVIR environment, the fact that the weld to be inspected is visually distinct from the surface of the reactor vessel can be used to constrain the robot to a known position with reference to the longitudinal axis of the cylindrical vessel. A visual weld tracking algorithm, designed and tested in simulation, used images acquired from a camera mounted on the robot and processed them to detect the weld. Given the geometry of the camera system, a steering direction was generated to constrain the robot to move along the weld.

Pattern Based Localization: Traditional reactor vessels have punch marks placed along the weld at regular intervals to distinctly mark the location of the weld on the reactor vessel surface. A global positioning system for the RVIR uses such punch marks as land marks to determine the position of the robot. This scheme uses visually distinct punch mark patterns along the weld at known locations, detected by a vision-based algorithm. When a unique pattern is detected, the position of the robot is known. An algorithm designed to detect the punch mark patterns was tested on sample patterns. The main steps in the algorithm were color cue based image segmentation, and several steps of filtering to detect the patterns. The algorithm was tested on several images from the test set. Specification of the punch pattern locations prior to reactor vessel production will permit this positioning system to operate properly.

Because it is possible for the RVIR to find itself in a position in which no weld seam can be viewed, a triangulation algorithm was designed which can be used to determine the absolute location of the robot. This system consists of a laser source and a photo detector mounted close together. A retro-reflector is mounted on the robot so that if a laser beam is projected on to the reflector, the reflected light will travel in the opposite direction of the incoming light. The laser source scans a plane using a rotating stage or a rotating mirror. When the reflected laser beam is detected by the detector, the angle between vertical and the robot can be calculated. By using two such systems, triangulation can be used to localize the robot since the distance between the two sources is known. Computer simulation results show that this system can satisfy the accuracy requirements.

WELD INSPECTION SENSOR

The ALMR reactor vessel environment also presents problems for the weld inspection task, itself, due to the material of which the vessel is constructed, to the emissive coating on the vessels, and to the presence of the argon atmosphere which must remain uncontaminated by couplants. Due to these characteristics, inspection of welds in the stainless steel reactor vessel of the ALMR requires use of a nonstandard ultrasonic system called the electromagnetic acoustical transducer (EMAT) sensor [1,2], which must be specially designed for the particular weld inspection being done. Weld inspections on typical light water reactor vessels, and on other welds in non-critical environments, can be done using more common ultrasonic sensors which use a couplant (either water or oil) to deliver the full power of the sound signal to the weld seam. Both the argon gas and the emissive coating preclude the use of such couplants in the ALMR.

EMATs systems produce special ultrasonic signals by using specially wound electromagnetic coils and rare-earth permanent magnets. These devices are sized and arranged to produce a signal which is tailored for the specific type of weld and vessel construction material. The characteristics of austenitic (stainless steel) material present numerous problems for detecting and characterizing weld flaws, due to the presence of non-critical variations in the welds and surrounding material. Therefore, use of EMATs technology requires a particularly tedious and carefully executed inspection regimin to be successful. The RVIR robot, with the EMATs system attached to the rear of the robot chassis, is capable of completing this type of weld inspection.

SUMMARY AND CONCLUSIONS

The RVIR consists of a chassis containing two sets of suction cups that can alternately grasp the side of the vessel being inspected. This system provides the needed mobility and directional control to permit the RVIR to crawl along the weld seam and carry out the inspection task. Most mechanical actions are servo actuated, using compressed gas. Most electronics are located off-board, and those that are on-board are shielded and cooled to preserve them from the harsh environment of the ALMR. Three cameras provide vision forward, up and down for navigation and for visual inspection of the vessels. Inspection of welds in the stainless steel reactor vessel of the ALMR requires use of a nonstandard ultrasonic system called the electromagnetic acoustical transducer, which must be specially designed for the particular weld inspection being done. The RVIR represents a robot designed for a restrictive application which can be used in a variety of less demanding applications. Further development of the RVIR will take place as funding and opportunity permit.

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