CONF-9405169--1

Engineering Physics and Mathematics Division

A WALL-CRAWLING ROBOT FOR REACTOR VESSEL INSPECTION IN ADVANCED REACTORS*

Philip F. SPELT
Oak Ridge National Laboratory, ms 6364, P. O. Box 2008
Oak Ridge, Tennessee, 37831-6364, USA

Carl CRANE
University of Florida, 300 Mechanical Engineering Bldg., CIMAR, Gainesville, Florida, 32611, USA

Liquang FENG
University of Michigan, 1101 Beal Avenue, Room 44
Ann Arbor, MI 48109, USA

Mongi ABIDI
University of Tennessee, Dept. of Electrical & Computer Engineering, Ferris Hall, Knoxville, TN 37992-2100

Sabri TOSUNOGLU
University of Texas, Dept. of Mechanical Engineering
26 San Jacinto, Austin, Teas 78712, USA

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

Manuscript submitted to AIR '94, Application of Artificial Intelligence and Robotics to Nuclear Plants, Tokai-mura, Naka-gun, Ibaraki 319-11, Japan, May 29-June 2, 1994.

---

* Research supported by the Office of Nuclear Energy, Office of Technology Support Programs, U.S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

A WALL-CRAWLING ROBOT FOR REACTOR VESSEL INSPECTION IN ADVANCED REACTORS*

Philip F. SPELT
Oak Ridge National Laboratory, ms 6364, P. O. Box 2008
Oak Ridge, Tennessee, 37831-6364, USA

Carl CRANE
University of Florida, 300 Mechanical Engineering Bldg.,
CIMAR, Gainesville, Florida, 32611, USA

Liquang FENG
University of Michigan, 1101 Beal Avenue, Room 44
Ann Arbor, MI 48109, USA

Mongi ABIDI
University of Tennessee, Dept. of Electrical & Computer
Engineering, Ferris Hall, Knoxville, TN 37992-2100

Sabri TOSUNOGLU
University of Texas, Dept. of Mechanical Engineering
26 San Jacinto, Austin, Teas 78712, USA

ABSTRACT

A consortium of four universities and the Center for Engineering Systems Advanced Research of the Oak Ridge National Laboratory has designed a prototype wall-crawling robot to perform weld inspection in advanced nuclear reactors. Design efforts for the reactor vessel inspection robot (RVIR) concentrated on the Advanced Liquid Metal Reactor because it presents the most demanding environment in which such a robot must operate. The RVIR consists of a chassis containing two sets of suction cups that can alternately grasp the side of the vessel being inspected, providing both locomotion and steering functions. Sensors include three CCD cameras and a weld inspection device based on new shear-wave technology. 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 non-radiation, room-temperature mockup of the robot work environment and shown to perform as expected.

---

* Research supported by the Office of Nuclear Energy, Office of Technology Support Programs, U. S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

I. INTRODUCTION

The Center for Engineering Systems Advanced Research (CESAR), sponsored by the Department of Energy (DOE) Office of Basic Energy Sciences, represents an engineering research 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 has been providing 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 has been 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 has consisted of utilizing and advancing state-of-the-art robotics technology through close interaction between universities, CESAR, commercial robot producers, and manufacturers and operators of nuclear power plants.

In 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. A new robot was designed and prototyped because none of the known wall-crawling robots met the needs required for weld inspection n the ALMR. 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 reactor vessel 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 decrease 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 performing the inspection. 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 meet the requirements of the ALMR ensures a robot that will perform in less demanding environments associated with, for example, the modular high temperature gas cooled reactor or the various advanced light water reactors.

II. CHASSIS DESIGN

During conceptual design of the RVIR, the team considered a number of wall attachment and locomotion mechanisms, 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 final choice of suction cups was driven by the need to preserve the emissive coatings on the outer surfac of the reactor vessel and the inner surface of the containmen vessel. The temperature and radiation levels dictated that a much of the electronics as possible be located off-board the robo and outside the immediate reactor vessel environment. Thos electronics which must remain on-board, such as the three vide cameras and the weld-inspection sensors, must be cooled, and mus either be radiation tolerant or be shielded.

The proof-of-principle prototype RVIR consists of a chassi containing two sets of vacuum suction cups that can alternatel grasp the side of the vessel being inspected. The RVIR chassis i shown in Figure 1 below. At the corners of the RVIR are fou suction cups which can slide on channels inside the chassis t permit the robot to walk forward or backward. These cups an their associated channel slides are shown as items a in Figure 1 Linear translation of these corner cups is accomplished by a electric motor-driven worm gear (item b in Figure 1). Thi apparatus provides about 10 cm of translation. A second set o three suction cups is attached to a centrally-pivoted plate unde the center of the RVIR chassis (Fig. 1, part c). This set of cup provides steering functions when the rotating servo device (Fig 1, d) is actuated. Each set of suction cups can be extended to o retracted from the surface on which the robot is crawling Extension and retraction of the sets of suction cups i accomplished by compressed gas cylinders (Fig. 1, f). When th sets are alternately extended and activated (vacuum applied), th RVIR's crawling or steering functions can be accomplished b either activating the linear translation system or rotating the

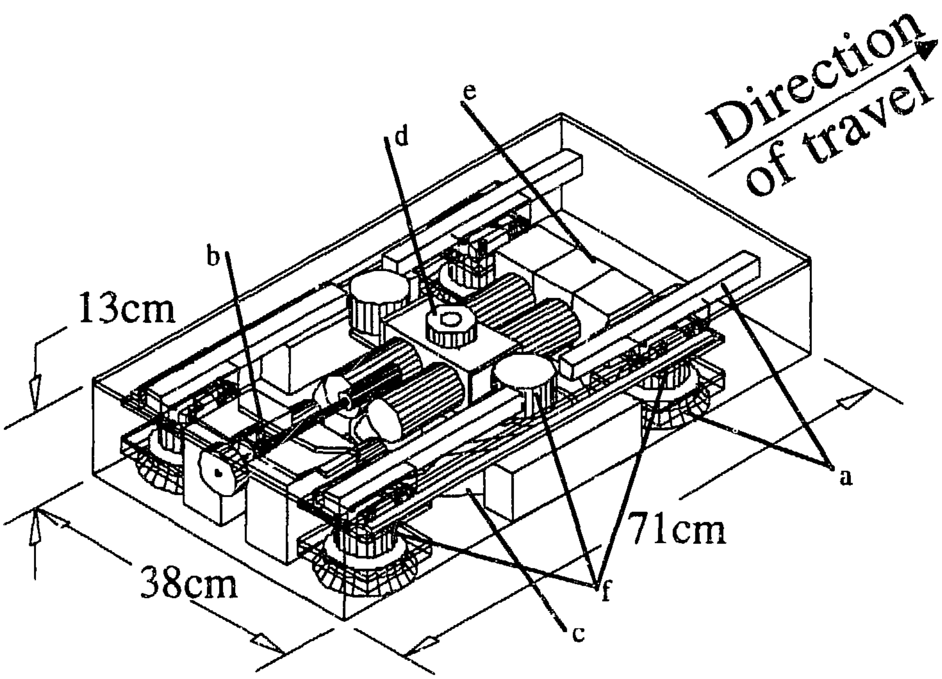

Figure. 1. RVIR cutaway diagram showing the linear (a) and rotary (c) suction cups, the steering servo (d) the suction cup extender servos (f), and the sensor box (e) toward the front.

servo turning device. Performing these individual steps in rapid sequence, under computer control, permits the robot to navigate around the surface of the vessel being inspected.

The 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 prototype meet both the temperature and radiation requirements, with the exception of the pneumatic servo valves and tether hose. These items are available to meet the environmental requirements, but were not used for the prototype due to budgetary constraints. Similarly, the compressed gas used to power the prototype was air, although the actual robot would run on compressed argon. Almost all electronics are located off the robot 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 on-board 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.

III. 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 hardware 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 by 7.0 cm by 2.7 cm. Each camera is equipped with a 380-line high-resolution array, automatic iris, internal synchronization, automatic shutter and low lux (<2 to 100,000 lux) 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. The three-camera sensor module configuration, shown in Figure 2, fits into the sensor module which is labeled as item e in Figure 1. In the view in Figure 2, "front" is up, and the top-looking camera is toward the right part of the assembly, with the bottom-looking camera out of sight behind the other cameras and the base frame. The forward-looking camera is oriented in the direction of RVIR travel, and the other two are oriented to the top and bottom of the RVIR. The camera which looks out the bottom is about 3.0 cm from the vessel on which the RVIR is crawling, while the top-viewing camera is about 9.0 cm from the other vessel. The focal lengths and other visual characteristics of these cameras are modeled in a simulation which permitted performance evaluation of the 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. In existing reactor vessels, a punch-marking scheme is used to identify the welds. For the ALMR application, a special punch system has been proposed which would permit determination of the RVIR location according to the particular pattern it encounters. Such a system would consist of either a simple numerical coding scheme, or one based on the Braille numeral patterns. Several image sequences of numerical and Braille-code pattern weld markings were taken by the front-facing and the down-facing cameras in the simulation. These patterns were used to help design the size and interval of the weld-marking patterns to make the inspection task easier to perform.

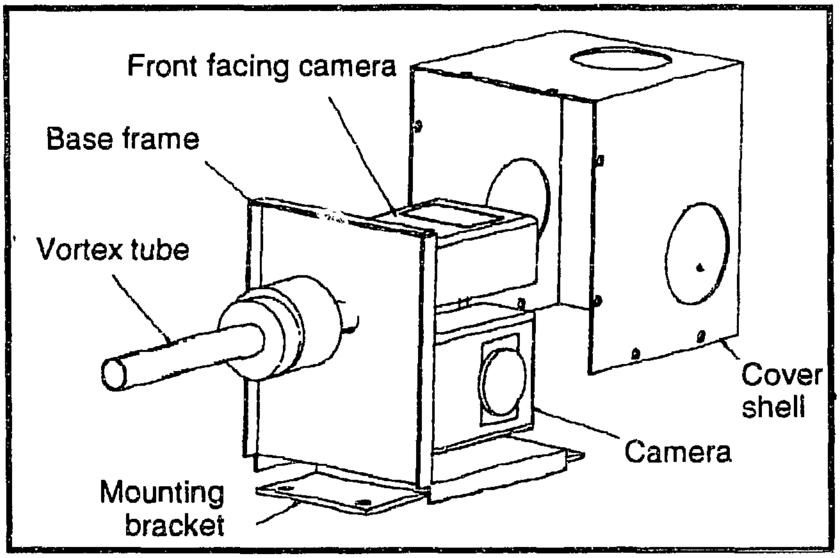

Figure 2. Sensor box showing the three CCD cameras with mounting bracket, vortex tube, and cover with camera windows.

IV. SENSOR MODULE DESIGN AND TESTING

Although many heat-resistant components exist, not all sensors have such robust versions, and when they are available, prices tend to be considerably higher than standard equipment. Hence, development of a capability to actively cool critical equipment is necessary. For this purpose, three cooling system design alternatives were considered: forced convection, air conditioning (AC), and vortex tube technology. Forced convection is not effective in high temperatures, since the cooling air would be heated during transition down the tether hose. AC is a complicated mechanical system which is subject to breakdowns, and it would add considerable weight to the RVIR. Therefore, employment of a vortex tube was determined to be the most suitable option. As shown in Figure 3, vortex tubes are simple devices which convert the compressed gas into two flows: one hot and one cold. The appeal of the vortex tube technology is that it is a simple design with no moving parts, operating only on compressed air (or argon), with no other power required.

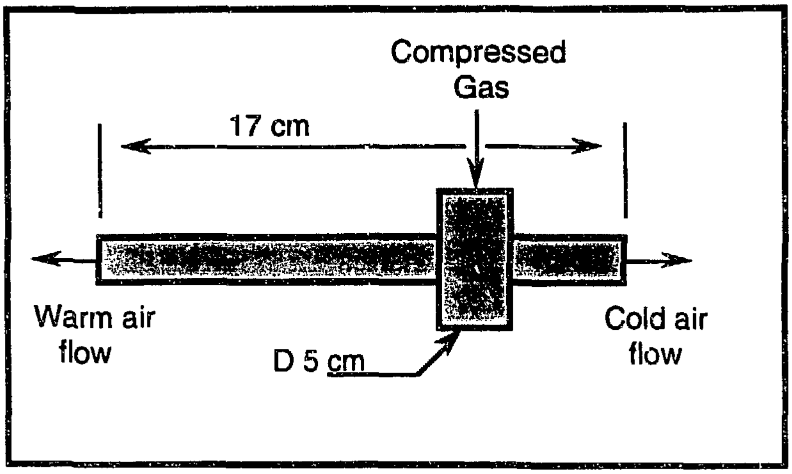

FIG. 3. Diagram of Vortex tube technology.

A vortex tube operating with 2.8 m^3/min. of compressed inlet air 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 from about 30 W to over 1700 W. Other advantages of a vortex tube include the fact that operation with argon improves system efficiency; air flow rate and the resulting temperature can easily be adjusted; and the vortex tube is effective for cooling enclosed volumes such as the sensor box on the RVIR.

Although the weld inspection devices (see below) and other sensitive electronic equipment on board the robot will be enclosed by the sensor module, the current prototype version of the RVIR requires only the enclosure of the three CCD cameras. For this purpose, a camera module was developed which allows easy assembly and disassembly of the module for maintenance and camera or lens replacement, as shown in Figure 2. Structurally, the sensor module consists of two pieces: a base frame with two sides which mount the CCD cameras and the vortex tube; and the cover shell with four sides, three of which contain windows for the camera lenses. The module's outer shell is constructed from thin steel sheet, and is insulated from the inside by two layers of aluminum paper, which has excellent insulation properties. Outer dimensions of the module are approximately 9.8 by 12 by 12 cm, and it weighs about 1.96 kg. including the three cameras, vortex tube and all attachments.

An experimental testbed, shown in Figure 4, was developed to test the performance of the sensor module and the vortex tube cooling system. While the sensor box was heated in a furnace, its interior was cooled by the vortex tube (Model 208 by Vortec Co.). Thermocouples located inside and outside of the module sent the temperature readings to the computer for recording and analysis. During the tests, when the outside ambient temperature was 211°C, module interior temperature remained at 14°C, which is quite satisfactory. These temperature profiles are plotted in Figure 5

Spp146

as a function of time in the test chamber. In order to assess the effectiveness of the vortex tube, a similar test was run without the vortex tube. Instead, only compressed air at 6.9 X 10^5 Pa was

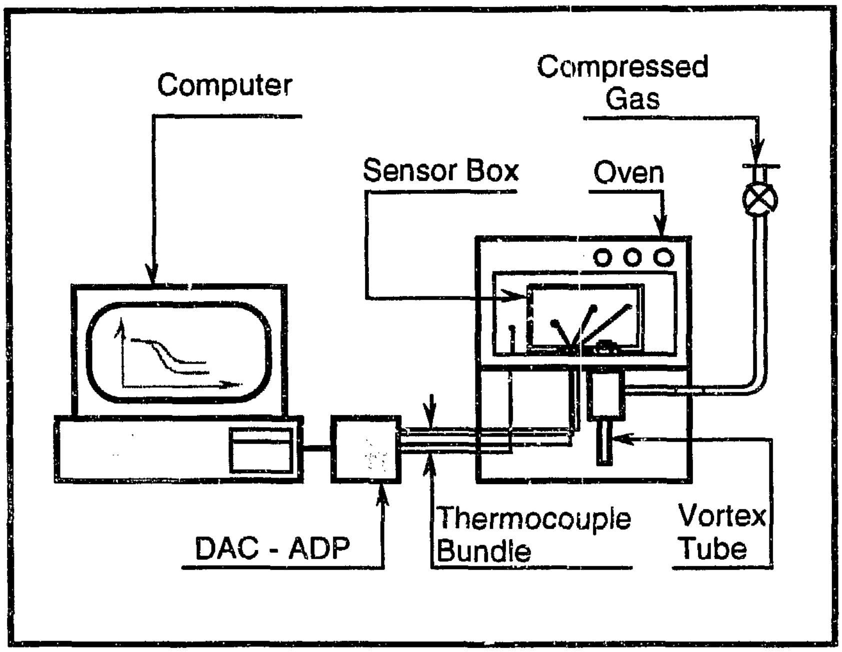

Figure 4. Experimental test bed to examine the relative efficiency of convection cooling and the vortex tube.

supplied to the sensor module. During this test, module interior temperature rose to 49°C in 12 minutes. Since the cameras can not operate above that temperature, the test was terminated. These

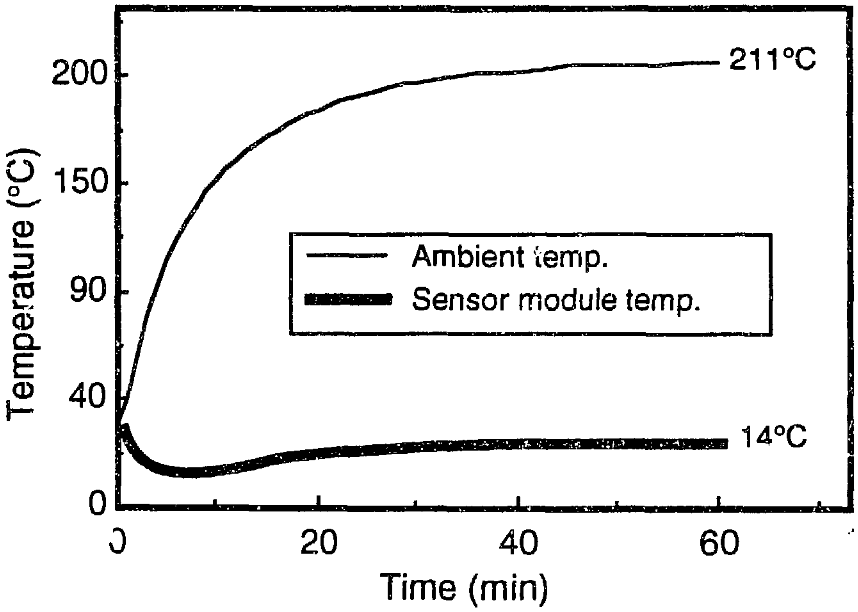

Figure 5. Temperature comparison of the sensor module and the oven chamber as a function of time.

results demonstrate the effectiveness of the vortex tube over just using compressed air in this application. More generally, these tests indicate that vortex tubes may be used successfully to cool sensitive electronic components enclosed in relatively small volumes.

V. NAVIGATION

The navigation problem consists of two major parts: weld tracking and fault localization. For weld tracking, the task of the robot is to inspect the welds both along the circumference of the reactor and containment vessels and the vertical welds between the circumferential welds. This task requires the design of algorithms which generate steering commands to achieve weld following. Fault localization involves detecting a fault on the weld. Once a fault is detected, the robot must be able to report the location and orientation of the fault precisely.

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 to detect the weld. Given the geometry of the camera system, a steering direction can be generated to constrain the robot to move along the weld.

As mentioned above, 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 taken from an existing light water reactor vessel. 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 perform quite accurately.

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 locate the robot, since the distance between the two sources is known. Computer simulation results show that this system can satisfy the accuracy requirements.

VI. WELD INSPECTION SENSOR

The ALMR reactor vessel environment also presents problems for the weld inspection task due to the material of which the vessel is constructed, due to the emissive coating on the vessels, and due to the presence of the argon atmosphere which must remain uncontaminated by couplants. Because of 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. However, both the argon environment 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, successful use of EMATs technology requires a particularly tedious and carefully executed inspection regimen. The RVIR robot, with the EMATs system attached to the rear of the robot chassis, is capable of completing this type of weld inspection.

VII. 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 EMAT, which must be specially designed for the particular weld inspection being done. The RVIR represents a robot designed for an application under very harsh environmental conditions. It can be used in a variety of less demanding applications.

Spelt?

REFERENCES

1. Alers, G. A. and L.R. Burns EMAT desings for special applications. Materials Evaluations,45, October, 1987, 1184-1189.

2. Maxfield, B. W., A. Kuramoto, and J. K. Hulbert Evaluating EMAT designs for selected applications. Materials Evaluations,45, October, 1987, 1166-1183.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Spe 14+10