MOBILE ROBOTICS FOR CANDU REACTOR MAINTENANCE: CASE STUDIES AND NEAR-TERM IMPROVEMENTS

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ABSTRACT

Although robotics researchers have been promising that robotics would soon be performing tasks in hazardous environments, the reality has yet to live up to the hype. The presently available crop of robots suitable for deployment in industrial situations are remotely operated, requiring skilled users.

This talk describes cases where mobile robots have been used successfully in CANDU stations, discusses the difficulties in using mobile robots for reactor maintenance, and provides near-term goals for achievable improvements in performance and usefulness.

1. INTRODUCTION

The advantage of using a robot for inspection and maintenance is that a robot can gather information and do work in highly hazardous areas. In such areas, and to a lesser extent in inaccessible areas, conventional remote sensors and tooling can not be deployed. Information gathered by robots about the hazards can be used to rehearse procedures, which reduces dose during the task. In some cases, simple gripping and actuation tasks can be done by the robot instead of by a human, allowing tasks to be done in inaccessible areas quickly, cheaply, and safely.

Robots for CANDU maintenance fall into two categories: mobile vehicles and portable manipulators. The mobile robot is most useful for delivering sensors to a highly hazardous location to gather information. The portable manipulator is used for jobs with a limited work space where hazards are local.

As well, the fueling machine can be used as a robotic tooling delivery system at the reactor face.

1.1. Mobile Vehicles

Mobile robots with manipulators are in use at Ontario Hydro CANDU stations. All share similar characteristics: they are wheeled or tracked machines with simple manipulator arms. The user drives to a location of interest to survey a scene remotely with video cameras, make a radiation survey, or perform rudimentary manipulation tasks. The robot is either tethered or self-powered and radio-controlled; the machine does not operate under automatic control.

One model has been modified to be carried by crane to a location; most models can ride elevators and operate buttons. Some models can climb stairs or crawl in pipes.

Pipe inspection robots are tethered, remotely operated tracked vehicles that crawl through pipes looking for abnormalities with on-board video cameras and lights. These mobile robots are built for small spaces and for moving along pipes with low flow. The Babcock & Wilcox (B&W) ROVVER and the Inuktun SEAMOR have been used at Pickering; SEAMOR is a submersible robot suitable for 20-inch pipes; it can also act as a conventional mobile robot when fitted with a small manipulator for object retrieval[1].

A Remotec Andros robot has recently been acquired by Darlington. This robot has articulated tracks for climbing catwalk stairs. Bruce-A and Bruce-B use Pedsco wheeled mobile robots.

The Pedsco at Bruce-B has already done remote visual inspections of equipment in hazardous environments, made radiation surveys, retrieved pieces of failed equipment, and monitored a maintainer's progress on a job without dosing another maintainer.

1.2. Portable Manipulators

Portable manipulators are used mostly in the bowls on the primary side of CANDU steam generators. This is an appropriate workspace because work inside the bowl does involve dose, but equipment can be brought to the boiler easily. Ontario Hydro has been using a Vermatt-Technics Flexivera manipulator with ABB-CE tooling for tube plugging. This portable robot arm is assembled inside the bowl in sections and remotely controlled from outside containment[2]. Zetec and B&W also make steam generator robots, which reach through the manway for faster set-up and removal. Such manipulators can be used to deliver other tools for tube inspection and repair. No robotic systems are presently in use on the secondary side of the boilers; water lances (such as those used by B&W) are articulated flexible probes, not robots.

ANDREA (manufactured by B&W) is a non-mobile, hydraulic manipulator for inspection and simple maintenance tasks inside the PNGS-A calandria vault. CALVIN, another manipulator, was developed specifically for calandria vault inspection[1].

1.3 Fueling Machines

The fueling machine (F/M) itself acts as a robotic tool delivery system for pressure tube sampling by wet scraping and molding, CIGAR, SLAR, PIPE, and SLARETTE. This is an excellent example of using modular tools with a common delivery system. The fueling machine is the only permanently mounted robotic system in the CANDU reactor vault. Bruce-B is considering building a Universal Delivery System for delivering inspection tooling.

2. LIMITATIONS

Mobile robots have limited capabilities: the driver has to use video to see where to go; there is no map except in the driver's memory; the arm is not versatile; and power is limited.

2.1. Getting Around the Vault

The driver of the vehicle has to visualize what the machine is doing with only the feedback from video cameras. This level of sensing is adequate, provided that the driver can navigate to the place of work without collisions.

Robots have not been used for other remote tasks because it is difficult to deploy the machine to some parts of the vault. Presently, the Bruce B robot enters through the transfer chamber or goes into the reactor vault on the fueling machine transport trolley. But interlocks prevent the crane from approaching close enough to the reactor face to engage the lifting bar on the robot to lift it to higher elevations.

Because of the limitations of using fuel handling equipment to get the robot into the vault, alternative strategies for entry into the vault have been proposed, such as going through the airlock. Operational procedures have to be reviewed before robots can be allowed to enter an airlock while the reactor is on-power; one option is to erect a temporary third doorway to maintain an airlock even when one door is open. An additional concern at Bruce-B is that the airlock doors and pressure equalization mechanism are manually operated, and the robot is not capable of opening and closing the airlock by itself. A worker may have to drive the robot through the airlock.

2.2. Autonomous Navigation

Much recent robotics research effort has focused on enabling a mobile robot to navigate by itself[3,4]; but autonomous navigation is not necessary for the type of specialized CANDU maintenance tasks that mobile robots will be doing in the foreseeable future. It is sufficient that a robot vehicle can be driven by the user without colliding with anything, and that it can backtrack when necessary. The onus is on the driver to keep track of where the machine is at a given time. Users of mobile robots practise to sharpen their orienteering skills as well as their driving technique.

The driver has to communicate over a tether or a radio link. Radiation fields have not interfered with radio communication or control in the fueling duct under reactors at power; communication in the vault itself while at-power has not been attempted.

2.3. Manipulation

Once the robot has reached the work site, the task is to make measurements or to manipulate a tool to do work. The manipulator arm is used to move a camera, an instrument, or a tool in a small work space. The arm is joint-controlled, which means that the user has to move the individual joints with joysticks and use video for feedback. This method of open-loop control makes dexterous handling very difficult and tiring. The robot arm can not handle a large payload. There are few sensors or tools that can be changed in the field to do different kinds of tasks.

In cluttered work areas, it would be advantageous for users to have closed-loop control for accurate positioning. Range imaging system can also be used to calibrate a scene[4]. But users do not need telepresence or fancy displays: they need machines that can do a small set of tasks reliably.

2.4. Power Supplies

An untethered robot must either drag an extension cord, or it must carry its power supply on-board, which limits the robot operation time. Recharging stations are not available inside containment. It matters little if the machine is retrievable from the vault immediately after the job, provided that the robot is secured and does not interfere with the operation of the reactor, up to and including the time that the robot can be retrieved.

3. CASE STUDIES

3.1 Fueling Machine Failure Diagnosis

In March 1992 at Bruce Unit 8, the Northeast fueling machine became stuck on a channel while attempting to replace a closure plug. The diagnosis of a charge tube drive failure was confirmed only after the Bruce-B mobile robot was sent to investigate[5].

From the East Service Area (ESA), the robot was driven through the transfer chamber and brought to the bottom of the stairs. The robot drove along the fueling duct, controlled by a maintainer in plastics in the ESA operating by radio control with video feedback. The robot had no problems with communications or with negotiating pipes in its path as it drove under Unit 8 while the reactor was at full power. The robot found the charge tube axial drive shaft in the fueling duct where it had fallen. The robot picked it up with its gripper and carried the shaft back to the ESA.

The robot thus confirmed the fault diagnosis and eliminated the need for a dose-intensive inspection and survey. Knowing the exact cause of failure allowed preplanning and rehearsal of the repair. During the actual repair, the robot monitored dose and provided visual feedback so that the maintainer could be coached.

3.2 End Fitting Visual Inspection

A CCD video camera was mounted on a Bruce-B F/M carriage to make a visual inspection of all end fitting sealing faces on the reactor face. The F/M was programmed to pass along all end fittings with an offset to align the camera. Video output was tape recorded for later inspection, which revealed pitting in the bottom segment of many sealing faces.

3.3 Leak Sealing of Shield Tank Wall

The SEAMOR robot was used as a robot submarine for inspection and leak sealing of the PNGS-A shield tank wall. The robot was tethered with an air-line driven motor for brushing an area clean and applying epoxy. The epoxy was mixed outside, so the robot had to apply the coating within twenty minutes. The robot carried its thirty pound payload using foam for neutral buoyancy. This robot was also used for underwater inspection of a trolley in the fuel bay, and in screen houses to examine the extent of zebra mussel infestations.

3.4 Radiation Surveys on Open Channels

During maintenance on open channels, radiation surveys have been made by the Bruce-B robot on a mini-platform on top of the carriage, mapping the beam and doing inspections into the channel. A CCD camera can be used in high fields; although a standard CCD camera has a nominal cumulative dose limit of 20 kR, often a camera will recover its sensitivity. A gamma meter is mounted onto the side of the arm with a separate video camera dedicated to reading that meter.

3.5 Valve Inspection from Inside Pipe

In most cases, inspections inside pipes can be done with video scopes or fiber scopes without having to open the pipe network. But these instruments require an access opening close to the area of interest. The submersible SEAMOR robot once traveled on tracks inside a 2-foot line to make an internal visual inspection of a broken valve.

4. ENHANCEMENTS

Rather than redesign a new machine, we propose that commercial mobile robots be modified to improve their performance and usefulness in CANDU stations.

4.1. Modular Tooling and Instrumentation

The arm has to be able to release an end effector and pick up another when it needs a different tool. The robot therefore needs a tool changer for instruments and tools, with a standard mount with positive lock and a connector for power and signal conductors. Examples include tools to collect smears or collect grab samples, custom grippers, tools for fasteners, leak detectors, and gamma meters.

4.2. Improved Communication Link

The user interface has to be able to read the modular sensors and actuate the modular tools. The communication link has to accommodate the range of tasks the robot can perform remotely. Existing systems will require upgrades. Using a penetration for radio transmission would improve reception. The radio transmitter must not affect reactor operation.

Electronics can be designed for high radiation fields; of mobile robot vendors, only Remotec specifically offers that option for its controller hardware. The controller architecture should be open for expandability and reconfigurability, but that is not a requirement.

4.3. Improved Power Supplies

Mobile robots can operate over a tether or by radio link with batteries. A recharge adapter would allow an untethered robot to operate longer inside containment. The adapter would be held in an end effector and would plug into a mains receptacle in the vault.

4.4 Modular Improvements to Manipulator Arm and Vehicle Base

Different tasks require different performance abilities, driven by task expectations. Modular subsystems allow the machine to be reconfigured to perform the job at hand. Figure 1 shows how a modular system might be configured. Improved arms will have less backlash, more power, and improved dexterity for maintenance tasks on complex parts in cluttered environments; for inspection, however, no major modifications to the arm are necessary. In all cases, the components must be rugged, corrosion-resistant, and washable for decontamination.

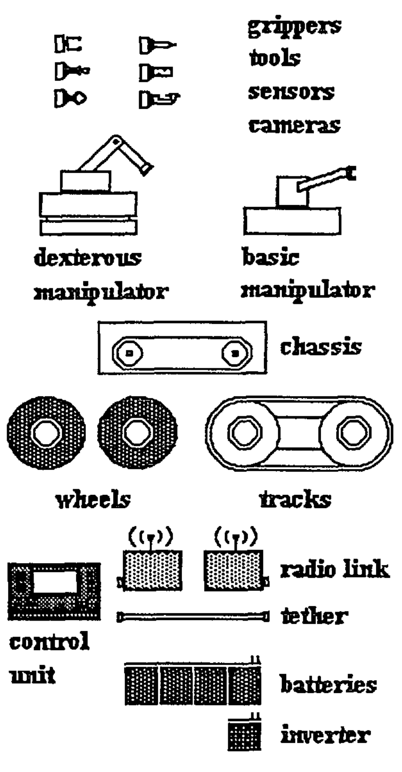

Figure 1: Modular Mobile Robot

5. TARGET APPLICATIONS

5.1 Maintenance Support

Target applications for the improved system include: inspection programs (both while on-power and during shutdowns) and testing of environmental conditions in different areas of the reactor while on-power to gather data for environmental qualification.

5.2 On-Line Operations Support

An application for robotics should provide more feedback into the condition of an area where there is little information available by other means. Inaccessible areas with little or no instrumentation are primary target areas. There are clear benefits to providing an operator with the means to find out the condition of equipment in containment that is not well instrumented. A mobile robot can be driven to a piece of equipment so that condition monitoring could be done on-line using video and audio inspection, or existing vibration and thermographic analysis techniques. This level of support for operations is achievable using existing technology with little additional development.

Using mobile robots for autonomous remote inspection and maintenance tasks remains a near-term dream until manipulators have: more degrees of freedom to be dexterous, joint sensing for closed-loop control, reliable controllers, an accurate ranging system for workspace geometric modeling, a user interface that is easy to use, and an automatic method of avoiding collisions in a cluttered work space. None of these necessary characteristics is available off-the-shelf, but they are all achievable with today's technology. For today's maintenance problems, however, mobile robots should be modified incrementally for reliable teleoperation rather than autonomous operations.

5.3 Fuel Channel Replacement

The most important area for robotics to be used in reactor maintenance is in fuel channel replacement.

To maintain fitness for service of fuel channels economically, channels must be replaced without long outages. The way to do this is to change several channels during each outage, thus maintaining the integrity of the pressure tubes. Single channels can now be replaced in fifteen days, but the time and the dose to workers could be reduced by automating most of the tasks, which keeps workers away from the face and reduces the need for building temporary shielding structures (a major dose task in itself). The existing fueling machine bridge and carriage should be used as the delivery system for robotic tooling for fuel channel replacement and refurbishment of end fittings.

Figure 2 shows how a robotic fuel channel replacement (RFCR) system can be implemented.

Remotely operated tools comprise three modules that attach to the F/M carriage. The old pressure tube (P/T) is removed by machining the end fitting (E/F) rolled joint (R/J) area with a larger diameter in one E/F to allow for annulus spacer clearance and installation of the new pressure tube. End fittings are not removed, which eliminates the need for bellows welding. The E/F R/J is made using a composite insert and a heavy P/T wall at the opposite end.

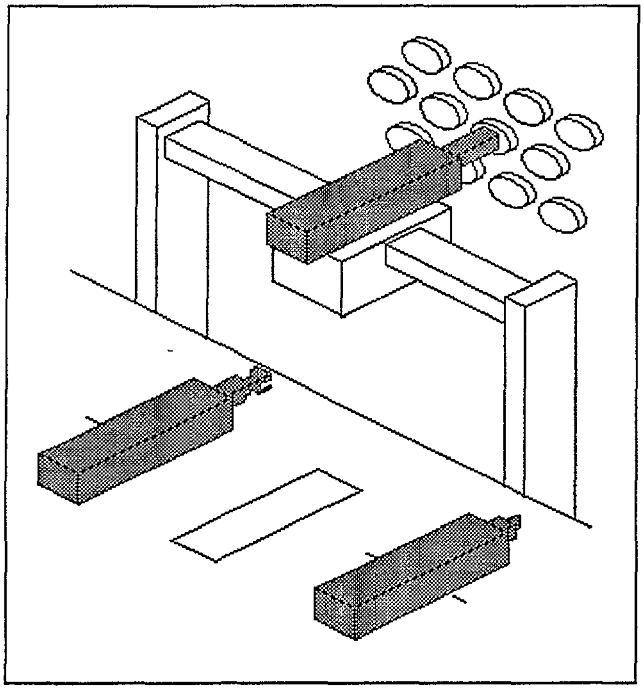

Figure 2: Robotic Fuel Channel Replacement System Concept

Implementation of robotic tooling can be incorporated into single fuel channel replacement (SFCR) campaigns as the tools become available, so that the system has an early impact on reducing SFCR time and dose. An immediately useful application would be to resurface end fitting sealing faces. In this way, the system can be developed and used promptly, the design remains closely tied to user requirements, and the system can be upgraded as required.

6. CONCLUSION

The near-term goal of modifying mobile robots for use in CANDU maintenance should not be to produce high-performance teleoperation systems. The goal should be to implement a series of incremental improvements. Each improvement moves toward higher performance and versatility, but utility and reliability should be added to mobile robots while keeping them available for maintenance tasks. In this way, mobile robots can assist in maintenance in radioactive areas so that it can be done more safely, in less time, and with less radiation exposure to workers.

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