HYDRO-QUÉBEC INSPECTION ROBOT FOR PHTS FEEDER PIPES SUPPORTS

Jean Lessard[1], Eric Lavoie[1], Stephan Beauregard[1], Jacques Côté[1], Régis Houde[1], Daniel Lapierre[1]
Alain April[2], Alain Drolet[2], Pierre Gauthier[2]

1- Institut de recherche d'Hydro-Québec
1740, boul. Lionel-Boulet, Varennes (Québec) Canada J3X 1S1
lessard.jean@ireq.ca

2- Hydro-Québec, Centrale nucléaire Gentilly-2
4900, boul. Bécancour, Gentilly (Québec) Canada G0X 1G0

ABSTRACT

This paper will briefly present Gentilly-2 Inspection program for the PHTS feeder pipes supports. The focus of the paper will be on the Inspection Robot technology developed by Hydro-Québec for that purpose and on highlights of the '97 to 2000 outage inspection campaigns.

The Inspection Robot consists of a probe installed at the end of a positioning arm with 5 degrees of freedom (d.o.f.) operating up to 45m (150') from the control and data-recording station. The control station provides the robot operator with auxiliary camera viewpoints and position feedback of the robotic arm. A typical probe has 2 axes of rotation and is equipped with a video colour camera, powerful lighting, and optionally a laser to do point to point measurements. The modular design enables to reconfigure the positioning arm to meet the requirements of a new inspection site.

The main advantages of using this equipment is a major reduction in radiation exposure, the high quality of the data collected and inspection data archiving for further analysis and reports.

INTRODUCTION

The Gentilly-2 CANDU-6 PHTS outlet feeder pipes are thinning because of the Flow Assisted Corrosion (FAC). As the FAC thinning is progressing, the remaining wall thickness of a few feeders is getting closer to their acceptable minimum. One of the hypothesis used to establish the minimum acceptable thickness of these pipes is that the feeder pipe supports are in good working condition.

PIPE SUPPORTS INSPECTION PROGRAM

There are about 7 to 8 km of piping on a CANDU-6 feeder pipe work and about 5 000 collars part of many hundreds of supports of many types are used on this piping system.

In 1996, excessive thinning of outlet feeders was diagnosed at Gentilly-2 and cracking of S08 elbow occurred at PLGS. Since then G-2 has put forward an exhaustive inspection program for feeder pipes and supports.

Amongst many other inspection activities like remaining wall thickness measurements, specific elbow cracking detection, etc., G-2 decided to develop a specialised inspection system in order to verify that the numerous pipe supports are still in good conditions and detect any anomalies requiring corrective maintenance.

So far, the annual inspection campaigns allowed the inspection personnel to verify the integrity of 75% of the cantilever beam supports, close to 100% of lower spacers, 50% of upper spacers and about 75% of seismic supports and dampers.

INSPECTION ROBOT SYSTEM

The Inspection Robot consists of a probe installed at the end of a positioning arm with 5 degrees of freedom (d.o.f.) operating up to 45m (150') from the control and data-recording station. A typical probe has 2 axes of rotation and is equipped with a video colour camera, powerful lighting, and optionally a laser diode to do point to point measurements.

The modular design enables to reconfigure the positioning arm to meet the requirements of different inspection sites. So far, three different configurations have been developed.

Lower Reactor face configuration

This configuration was the first to be developed. Its design is based on a standard positioning robot and the motion range of the axes are set to cover a large inspection site (see table 1).

One of the most important feature of this system relies on its modular design that makes it very easy to assemble and to dismantle in its basic modules. This particular configuration has four basic modules: the base, the mast, the boom and the camera probe.

Robot axes	Motion Range
Base Translation	185 cm
Base Rotation	360°
Mast Elevation	160 cm
Boom Forward	150 cm
Elbow Rotation	210°
Probe Pan	210°
Probe Tilt	210°

Table 1: Motion range for lower reactor face configuration

This configuration is used to inspect the following types of supports:

-Cantilever beam and eye-rod link
-Lower spacers(spreading blocks)

Figure 1: Pan & Tilt camera probe

The camera probe shown in Figure 1 has two axes of rotation organised in a Pan & Tilt configuration. In its zero position the point of view from the camera is aligned with the forward motion of the boom which makes it easy to operate during the inspection process. The overall size of the probe is less than 4 cm by 4 cm by 10 cm long. The camera head is fit with a ¼ inch CCD colour camera, four halogen lights and an optional micro laser diode for point to point measurements as described in the *3D Measurement* section below.

Upper Reactor face configuration

This configuration is a very similar to the previous one. In fact, the only difference is the length of the link between the boom elbow and the probe, and the length of the boom forward motion which are smaller.

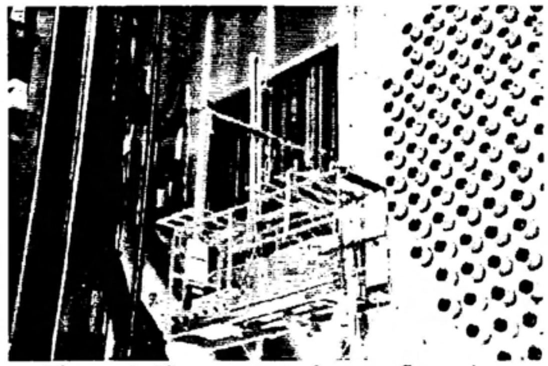

Figure 2: Upper reactor face configuration

These modifications were made necessary to avoid collisions between the robot and the FM bridge column when the robot is moved backward to move to the next insertion between two rows of feeders (see Figure 2 and Table 2).

This configuration is used to inspect the following types of supports:

-Upper spacers (spreading blocks)
-Distance measurement between feeder and spacer links

Robot axes	Motion Range
Base Translation	185 cm
Base Rotation	360°
Mast Elevation	160 cm
Boom Forward	110 cm
Elbow Rotation	210°
Probe Pan	210°
Probe Tilt	210°

Table 2: Motion range for upper reactor face configuration

Catwalk insulation cabinet configuration

As can be seen in Figure 3 and Table 3, this third configuration is very different from the previous ones. While the first three axes are very similar in all cases, the following two axes and two axes of the camera probe have been completely redesigned to meet the requirements of the inspection task in the catwalk insulation cabinet.

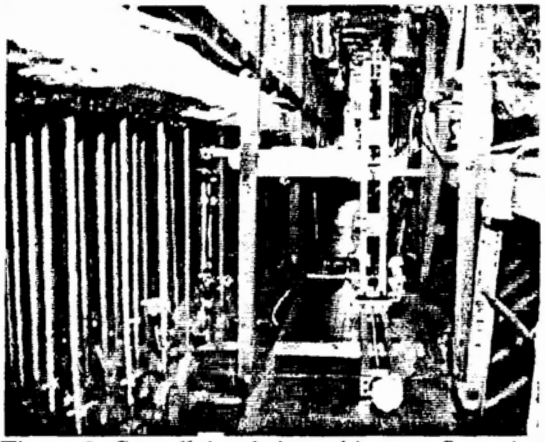

Figure 3: Catwalk insulation cabinet configuration

In this case, a major constraint is the limited space available to install the robot manipulator. While the width of the catwalk is about 60 cm the robot need to extend by more than 110 cm to reach the further yokes from the catwalk. Even more, the boom itself has extend downward in insertion slots sometimes smaller than 5 cm by 5 cm.

Robot axes	Motion Range
Base Translation	185 cm
Base Rotation	360°
Mast Elevation	75 cm
Boom Forward	113 cm
Boom Down	47 cm
Probe Pan	270°
Probe Tilt	-225° à +60°

Table 3: Motion range for catwalk insulation cabinet configuration

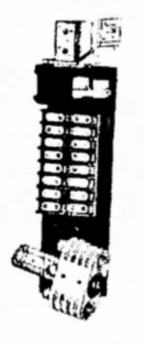

Figure 4: cabinet probe

This led to design the boom forward link as a three stages telescopic configuration instead of a long sliding link and the boom downward as a two stages telescopic link.

The probe is also oriented downward and the two axes of rotation have been redesigned to produce a natural Pan & Tilt motion to maximise camera mobility and ease its operation.

A second major requirement is the number of cycles that the robot has to perform to complete the inspection of the seismic supports and dampers on one side (north or south) of the reactor in such a tight overcrowded space.

The third major requirement is more specific to Gentilly-2 and is related to surrounding gamma radiation level at the catwalk level that can be as high as 1 rem/hre. So. this environment requires a very robust and reliable design including cabling protection and ultra fast replacement of the downward boom and probe module.

This configuration is used to inspect the following types of supports:

- Seismic support and yoke assembly
- Chafing sleeves & collars
- Seismic dampers & collars

Control and data recording station

The control station provides the robot operator with auxiliary camera viewpoints.

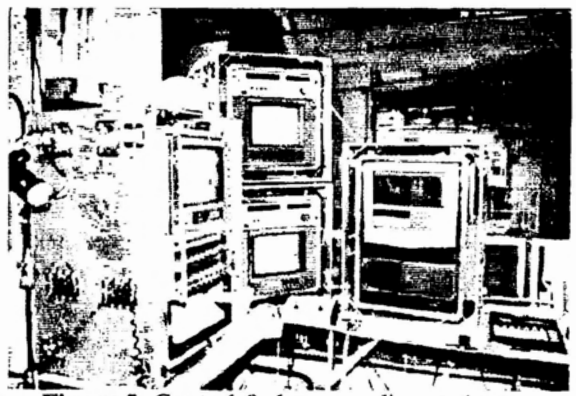

Figure 5: Control & data recording station

It also includes high quality videotapes (S-Video) and a PC-compatible computer providing the operator with position feedback of the robotic arm and data archiving of snap-shot images on CD-rom.

3D MEASUREMENT SYSTEM

The point to point measurement system is based on a micro laser diode located aside the camera and which beam is projected onto the object to measure. By triangulation and proper calibration, the position of the projected spot relative to the camera head can be computed. Since the camera head is mounted on a pan and tilt probe with encoder feedback, the position of different points of interest can be computed. The software gives the user some tools to measures distances between 2 points, between a point and a line and angles between two lines. These features proved to be useful in order to verify whether the pipe supports were in good condition or not.

Calibration

In order to recover position of the projected spot in the camera image, we need to calibrate the system. Even if most of the system parameters (baseline, laser angle, focal length, etc.) are known, a calibration will achieve better results since it could take into account unmodeled or erroneous parameters. The calibration process is achieved in two steps: depth calibration and lateral calibration.

We first want to obtain a relationship between the position of the laser spot in the image versus the distance of the spot from the camera. With a perfect camera (no lens distortion), this relationship would be:

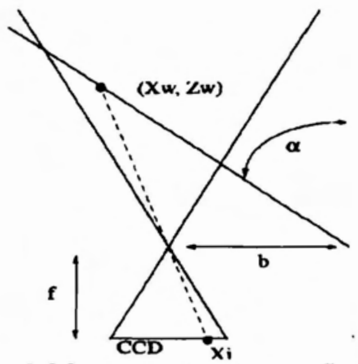

Figure 6: Measurement system configuration

$$Zw = \frac{fb}{f\tan(\alpha) - kXi} \quad \text{(Eq. 1)}$$

Where:

Zw = Z in world co-ordinate
f = focal length
b = baseline (distance between the laser and the camera)
α = laser angle
k = ratio between the X co-ordinate on the CCD and the X co-ordinate on the frame grabber (Xi).
Xi = position of the projected spot in pixel co-ordinate

Eq 1. can be written if the form :

$$Zw = \frac{1}{A - BXi} \quad \text{(Eq.2)}$$

The lens distortion in the X axis can be approximated by a second order function:

$$Xd = Xi - dXi^2 \quad \text{(Eq.3)}$$

Eq 2 become:

$$Zw = \frac{1}{A - BXi - CXi^2} \quad \text{(Eq.4)}$$

Classical curve fitting method (linear algebra or numerical optimisation) are then used to obtain parameters A, B and C from a set of experimental data.

The next step consists in finding the other co-ordinate Xw. This calibration is trivial since we know that the relation between Zw and Xw is a first order polynomial (a line).

$$Zw = mXw + b \quad \text{(Eq.5)}$$

$$Xw = \frac{Zw - b}{m} \quad \text{(Eq.6)}$$

In order to find m and b, we only need two sets of Zw and Xw :

$$m = \frac{Zw2 - Zw1}{Xw2 - Xw1} \quad \text{(Eq.7)}$$

$$b = Zw1 - mXw1 \quad \text{(Eq.8)}$$

The configuration used in the 1999 inspection campaign had a baseline of 39 mm, a laser angle of 21 degrees and a focal length of 2.2 mm. With this set-up, we could measure distance from 25 mm to infinity with a resolution of 0.7 mm at a nominal working distance of 100 mm.

TYPICAL INSPECTION PROCEDURE

The whole system has been designed to be easily moved from IREQ to Gentilly-2 power station or any other power plant. It can be brought up and be ready for inspection in a matter of a few hours after arrival at the power plant. When system check up is done the robot manipulator can be dismantled in its basic modules, moved at inspection site and brought up in less than an hour.

A typical detailed inspection time is two days (12 hours) per reactor face either for upper spacers or lower spacers and cantilever beam. On the other hand, it takes four days (12hours) per reactor quart for seismic supports and dampers, and chafing sleeves.

The main advantages of using this equipment is a major reduction (up to 10x) in radiation exposure (short set-up and retrieve time and remote operation), the high quality of the inspection data (colour S-Video) and inspection data archiving (S-VHS & snap-shot images recorded on computer and CD-rom) for further analysis and reports.

HIGHLIGHTS FROM PREVIOUS INSPECTION PROCEDURE

Since the 1997 outage, inspection campaigns were conducted for the following type of supports:

Cantilever beam and lower spreading bocks

Inspection results showed that there was no apparent sliding of the lubrite pad on most of north face cantilever beam supports. This resulted in a 10° to 15° eye rod link inclination. Some lubrite pads also appeared to be in bad shape.

All cantilever support eye rod links were straightened and tightened. A few lubrite pads were replaced.

The inspection data also showed that the eye rod link of S08N was not loaded. Subsequent verification revealed that some floor penetration of seismic rod hanger were rammed and a few were totally jammed. They were cleaned up using a custom tool.

Close to 100% of the lower spreading blocks were inspected and no significant anomalies were reported.

Upper spreading blocks

In 1998, one spreading block link was found in bottom of feeder insulation cabinet on the north face of the reactor. It was coming from the upper spreading blocks. A replacement link was installed.

The next year, a complete inspection of the upper spreading blocks of the north side was performed. Contacts during cold state of four spreading bar links against adjacent feeder were detected. Two contacts during hot state were also detected.

Bending of two spreading bar links was performed to get appropriate clearance. Traces of minor sliding, about half an inch, were found on a few spreading blocks.

The inspection of the upper spreading blocks on the south side of the reactor is planned for the 2001 outage.

Seismic supports and dampers

So far about half of the south side of the reactor has been inspected and the inspection of the north side has been completed.

A few kinds of anomalies were found for these supports and dampers. Most of them being minor, they did not required any intervention. The most frequent ones were the chafing sleeve collar laying right under yoke, free space (¼'' to ½'') between some dampers, upper row feeders laying against horizontal tie bar of hanger, contact between two yokes, displacement of yokes but still laying against chafing sleeve, collar on feeders and "U" bolts on feeders.

A few anomalies were detected that required intervention or that intervention are planned for. On the north side a total of seven yokes were found laying right against the feeder instead of laying in position against the chafing sleeve (see figure 7 for a typical example).

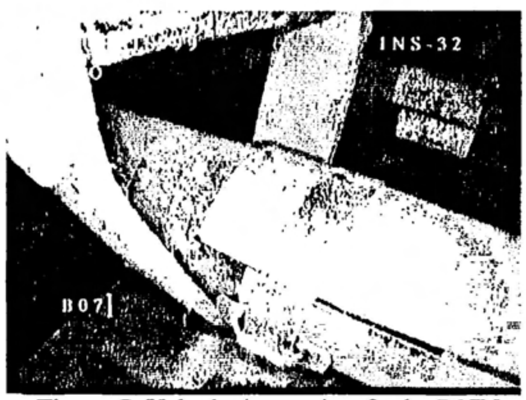

Figure 7: Yoke laying against feeder B07N

Some of them may have been installed improperly but a few of them appeared to have been moving over the years.

These yokes were put back into position by releasing the tension and tightening them in proper position. In a few cases, small fretting marks were found. In such cases these marks were smoothed using sand paper and no further evaluation or measurements were needed.

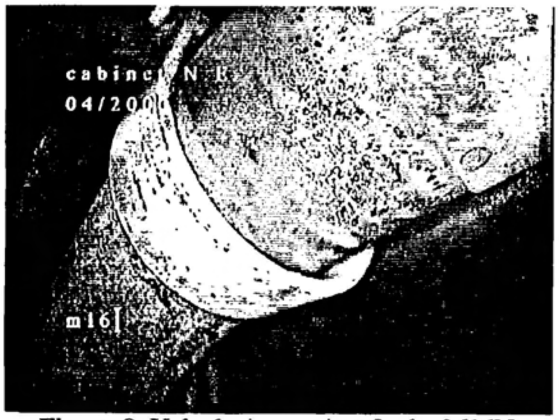

Figure 8: Yoke laying against feeder M16N

In one case, M16 (figure 8), the marks found were more significant (see figure 9). To evaluate more precisely these marks a calibrated videoscope with a stereoscopic lens was mounted on the robot. The data collected enabled to estimate the length the width and the depth of these marks.

Figure 9: Fretting marks found on feeder M16N

Finally, in one case a steel wire surrounding a feeder (T06) left fretting marks on the feeder.

Evaluation of these marks using either videoscope or a laser probe and removal of the steel wire are planned for the 2001 outage.

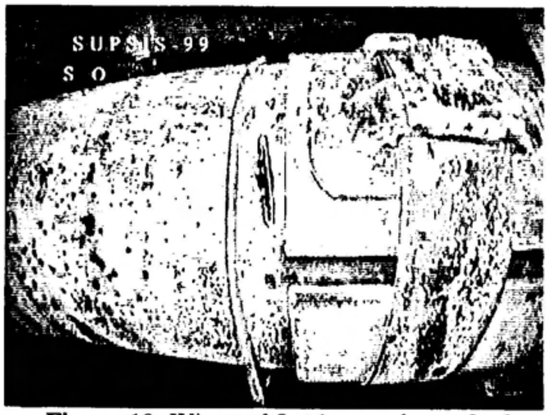

Figure 10: Wire and fretting marks on feeder M16N

CONCLUSION

The main advantages of using this equipment is a major reduction (up to 10x) in radiation exposure (short set-up and retrieve time and remote operation), the high quality of the inspection data (colour S-Video) and inspection data archiving (S-VHS & snap-shot images recorded on computer and CD-rom) for further analysis and reports

The inspection system has been very useful in identifying anomalies found inspecting the various supports and spreading blocks. In some cases interventions were necessary to assure the good working condition of the latter and the inspection robot was again used to verify that the interventions were successful and in some cases it was also used to assist workers performing those tasks.

TECHNICAL REPORTS

G2-RTI-2000-33126-33 Inspection télévisuelle des supports et amortisseurs sismiques (quadrants NE et NO), USI: 33126, septembre 2000.

G2-RTI-99-45 Activité de vérification et ajustement des supports et amortisseurs sismiques des TAR, USI: 33128, 19 aout 1999.

G2-RTI-99-46 Inspection des blocs d'espacement supérieurs des TAR, USI: 33126, 30 septembre 1999.

G2-RTI-97-36 Inspection des supports ainsi que des barres et blocs d'espacement des tuyaux d'alimentation du caloporteur, USI: 33126, 26 juin 1997.