HYDRO-QUÉBEC REC SYSTEM: PROBE POSITIONING SYSTEM FOR HEAT EXCHANGER INSPECTION

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Abstract – **In 2002, Hydro-Québec's Gentilly-2 (G2) Nuclear Power Plant commissioned the Hydro-Québec Research Institute to integrate its SCOMPI technology into their eddy current heat exchanger inspection system. The purpose of the project was to develop a fast, precise and reliable automated positioning device, which would be adaptable to several heat exchangers, including steam generators. Hydro-Québec's SCOMPI robot is a portable, six-axis robot, developed in 1992 for the repair and maintenance of turbine runners. Renamed the "REC system", the integrated SCOMPI robot was first used in 2003 to inspect moderator and shut-down cooler heat exchangers. In 2005, the newer MINI-SCOMPI replaced SCOMPI technology in the REC system, which was then used to inspect two G2 steam generators. MINI-SCOMPI is a smaller version of the SCOMPI that allows quick and easy one-man installation. Both the 2003 and 2005 inspection programs were successful, with REC system integration proving to be nearly transparent. No failures or lost time occurred during the inspections and all heat exchanger tubes were accessible. In addition, probe positioning was very efficient thanks to the MINI-SCOMPI and the vision system. The 5th CNS International Steam Generator Conference provides us with an excellent forum for presenting the successful integration of a new technology into an existing system for the inspection of various types of heat exchangers.**

I. INTRODUCTION

The Hydro-Québec Research Institute (IREQ), founded in 1967, is the core of technological innovation at Hydro-Québec. IREQ conducts research, development, testing and implementation of new technologies to provide reliable energy at the lowest possible cost. Generation, Transmission and Distribution, which are Hydro-Québec's main divisions, determine avenues for innovation based on their priorities and objectives.

An R&D project with IREQ and Hydro-Québec's Gentilly-2 Nuclear Power Plant (G2) began in 1997 with the development of a video inspection robot for the reactor face. That project now encompasses all inspection, maintenance and repair tool development carried out by IREQ in cooperation with G2, notably feeder inspection tools, a fuel channel inspection head, a feeder and depleted fuel line visual inspection robot, and a 3D CAD simulator. In this R&D program, G2 defines the priorities and objectives. G2 engineers specialize in instruments, methods, analysis and inspections. At IREQ, the Automation and Measurement Systems group specializes in mechanical, electronic and program design and integration, and provides technical support during inspections.

Through the years, G2 has developed its own heat exchanger inspection system in order to have a flexible tool, designed to inspect tubes in minimum time, at minimal cost and with good data quality. IREQ was one of its main collaborators, developing such tools for the inspection system as the probe-pushing program and device. In 2002, it was time for G2 to improve its automated probe positioning. At that time two systems were used, an accurate but slow one for steam generators, and a quick one for condensers, which was not easily adaptable, however, to exchangers with a circular tube sheet. G2 thus commissioned IREQ to develop a fast, precise and reliable automated positioning device, which would be adaptable to several types of heat exchangers, including steam generators. G2 was interested in the possible integration of Hydro-Québec SCOMPI technology into their eddy current heat exchanger inspection system. G2 had a thorough knowledge of the SCOMPI robot, which was entirely developed at IREQ. It is a portable six-axis robot, first used in 1992 for the repair and maintenance of turbine runners. The system is capable of welding, grinding and hammering.

After one year of development, the integrated SCOMPI robot, renamed the "REC system", was first used in 2003 to inspect moderator and shut-down cooler heat exchangers. In 2005, the newer MINI-SCOMPI replaced the SCOMPI robot in the REC system, which was then used to inspect two G2 steam generators.

II. G2 EDDY CURRENT HEAT EXCHANGER INSPECTION SYSTEM

For each outage, the G2 reactor inspection group has to inspect the tubes of several heat exchangers. Such inspections are very tightly planned among all the jobs performed during the outage. A precise schedule must be respected and a required number of tubes must be inspected. Through the years, G2 has developed its own eddy current heat exchanger inspection system, adapted to and suitable for the G2 exchanger family. The purpose was to have a flexible tool, designed to inspect tubes in minimum time, at

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minimal cost and with good data quality. This highly automated inspection system is spread across three locations: equipment in the periodic inspection building is linked by optical fiber to equipment in the reactor building, which is linked to tools performing the field inspection. The inspection approach involves inserting an eddy current probe inside the exchanger tubes. This probe is integrated with a data acquisition system and is chosen based on the exchanger to be inspected or the type of data to be acquired.

In the G2 inspection system, the probe moves down the tube being inspected by means of a push-pull device named “TP”. The TP program that controls the probe push-pull device is the heat exchanger inspection system manager, synchronizing all inspection tasks. The TP program triggers the probe-positioning sequence and data acquisition.

Data acquisition is performed during the pull sequence, as the probe goes back to its probe holder.

A probe-positioning device ensures probe alignement in front of the tube being inspected. This system is synchronized with the TP and therefore locked during the push-pull operation. Probe positioning is manual for most non-radioactive exchangers but there are two automated devices, one mainly used for condenser heat exchangers and one dedicated to steam generators. An automated probe-positioning device enables the automated inspection sequence to be performed for a complete list of tubes without human intervention. An inspection sequence has four main functions: the probe push-pull operation, probe positioning, data acquisition and data transmission for further analysis.

This last function is performed by the GDI monitoring program. All inspection data is available near instantaneously for analysis thanks to this program, which manages data transfer and storage, displays inspection performance and progress, and records special events. Only three to four operators are required to control the automated heat exchanger inspection system.

The inspection system also includes inspection planning and audio-video communication. Inspection planning is performed with the help of two programs, CARTO and ELI. CARTO is used to manage the G2 exchanger configuration database and ELI to display the exchanger tube sheet and to create lists of tubes to inspect. Those lists are then sent to the push-pull program.

In 2002, G2 expressed the need to further improve its probe-positioning system. The three existing probe-positioning devices were the manual system, the XY system and the COMAR system.

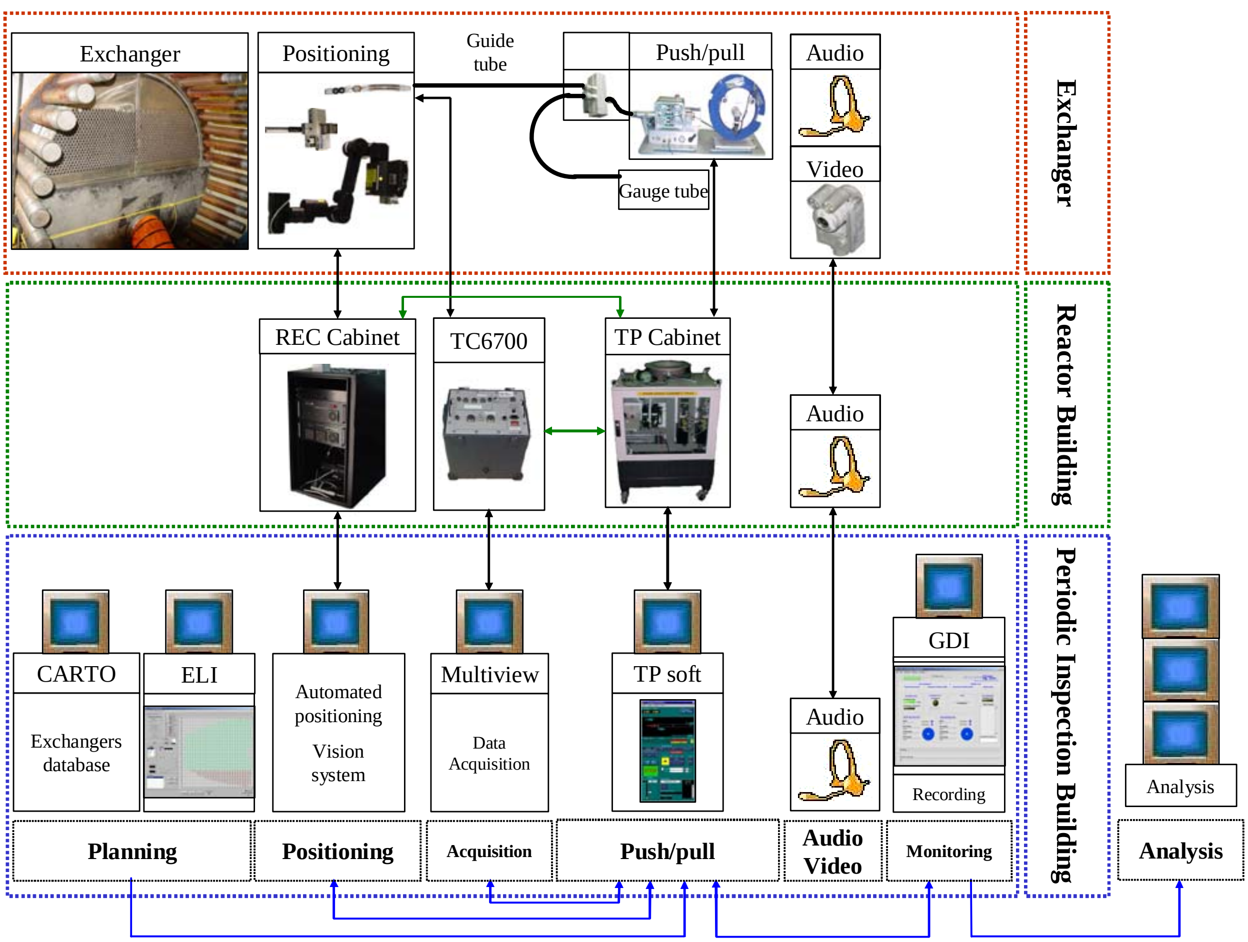

Fig. 1. G2 heat exchanger inspection system

A. *Manual probe positioning*

Manual probe positioning is used for almost all non-radioactive exchangers. It involves an operator placed in front of the tube sheet, who is in audio contact with the push-pull program operator and who moves a probe holder stick in front of the tube to inspect according to coordinates he receives verbally.

Fig. 2. Manual probe positioning

Manual positioning is highly flexible. The operator can easily adjust to the environment and the probe holder stick is the only equipment to be modified. Nevertheless, the positioning error probability is higher than any automated positioning system. Furthermore, manual positioning is not adapted to a radioactive environment.

B. *XY automated probe positioning device*

The XY automated positioning device was developed by the G2 inspection group in order to inspect the condenser and a few other heat exchangers. The condenser is not radioactive but each of its four water boxes contains seven thousand tubes, which makes manual positioning very difficult. The XY device consists of a two-axis positioning system: a sliding carriage on a horizontal track supports a probe holder, which can also move along a vertical axis. The track is fastened to the tube sheet by expanding clamps inserted inside the exchanger tubes. The device can be installed horizontally or vertically.

Fig. 3. XY automated probe-positioning device

The system is very easy to install and operate in XY coordinates. Its movements are quick and, combined with device compliance, are accurate enough to perform probe alignment. The system is perfectly suited for inspecting condenser heat exchangers but is not adaptable to exchangers with a fixed bowl and circular tube sheet. Steam generators are such a kind of exchanger, with many tubes which cannot be reached using the XY automated probe-positioning device.

C. *COMAR automated probe-positioning system*

The COMAR automated probe-positioning system has been dedicated to steam generators since the first inspections at G2. The COMAR device is a crawler which uses the steam generator tubes to cling to the tube sheet. Its two mobile plates, each equipped with four pneumatic clamps, step alternately to ensure COMAR device movement and probe holder alignment.

Fig. 4. COMAR automated probe-positioning device

The COMAR device is easy to install and very accurate but too slow for partial inspections or tube rescans. As the number of plugs increases, access to some tubes becomes problematic.

D. *New automated probe-positioning requirements*

Give the performance of its existing automated probe-positioning devices, G2 was interested in a new design, which had to be accurate, quick, easy to install, reliable and suitable for the entire G2 heat exchanger family. In 2002, G2 commissioned IREQ to integrate its SCOMPI technology into their eddy current heat exchanger inspection system.

After one year of development, the integrated SCOMPI technology, renamed the “REC system”, was first used in 2003 to inspect moderator and shut-down cooler heat exchangers. REC stands for “robot échangeur de chaleur” (heat exchanger robot). In 2005, the newer MINI-SCOMPI replaced the SCOMPI robot in the REC system, which was then used to inspect two G2 steam generators**.** The REC system is now fully integrated into the G2 eddy current heat exchanger inspection system and configurable for the inspection of different exchangers.

III. REC AUTOMATED PROBE-POSITIONING SYSTEM

Hydro-Québec’s SCOMPI robot is a portable, six-axis robot, developed in 1992 for the repair and maintenance of turbine runners. It has since proven its worth in numerous projects and harsh environments. The technology is entirely supported by IREQ. The SCOMPI robot has one straight and five circular axes. It is a multipurpose robot with welding, grinding and hammering capabilities. The

SCOMPI base system consists of the SCOMPI robot, a track, a pendant and a control cabinet containing a computer, a motor controller, a process controller and a main power subsystem.

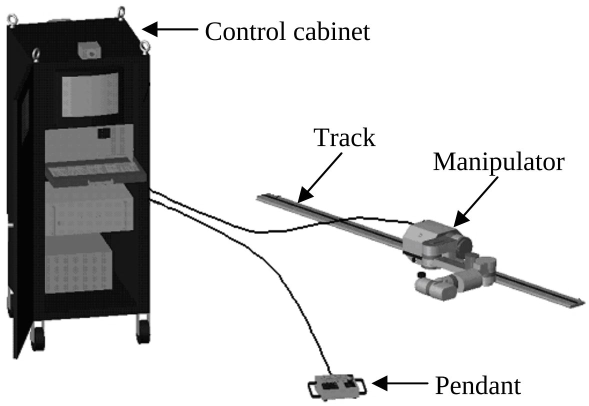

Fig. 5. SCOMPI base system

To be integrated into the G2 heat exchanger inspection system as part of the REC system, all components of this base system had to be modified, except the pendant. Development was a cooperative effort between G2 and IREQ.

A. *Control cabinets*

The G2 inspection system is spread across three locations, from the periodic inspection building where all control systems are located, to the inspected exchanger. In the SCOMPI base system, the maximum distance from control cabinet to manipulator is 120 feet (36.6 m). The control cabinet was thus split into two new cabinets. The first one is in the periodic inspection building. It contains the SCOMPI control computer and main power subsystem. A new control process was programmed interfacing the SCOMPI control computer with the push-pull program and offering a new user interface through the pendant, dedicated to heat exchanger inspection. A second computer dedicated to the vision system has been added to the first cabinet. The second cabinet is located in the reactor building and is linked by optical fiber to the first one. It comprises the motor controller, process controller and main power subsystem. The motor and process controllers are linked by 120-ft cables respectively to the manipulator and to a junction box interfacing all REC probe holder captors.

B. *REC robots*

The first robot integrated into the REC system was the original SCOMPI robot. As a REC robot, it was used in 2003 to inspect moderator and shut-down cooler heat exchangers. It weighs 33 kg with a 16-kg payload. It has undergone very few modifications to suit inspection requirements.

Fig. 6. SCOMPI robot

The second and latest robot used as a REC robot, is the MINI-SCOMPI, a SCOMPI replica on a 2:3 scale. This robot weighs 16 kg with a 5-kg payload. A smaller robot was the only solution suited to steam generator dimensions and inspection requirements. It had to be possible for a single operator working from the manhole to install the robot in the steam generator bowl. The robot also had to be able to reach all steam generator tubes. The SCOMPI was too big to achieve those objectives. The MINI-SCOMPI was the solution but required adjustments. First, a new clamping system was added to the carriage to make it easier to put the robot on the track with an outstretched arm and minimum visibility. Complete kinematic and dynamic inspection simulations were then performed to evaluate the required strength of each MINI-SCOMPI joint in order to meet the anticipated inspection constraints for all 3,542 steam generator tubes. These simulations led to changing motors, harmonic drives and sprocket ratios, and increasing from 40% to 60% the payload of four MINI-SCOMPI joints. In 2005, the MINI-SCOMPI, newly integrated into the REC system, was first used to successfully inspect from the inlet side half of the tubes on steam generators SG1 and SG2.

In the future, all heat exchanger inspections with the REC system will be performed using the MINI-SCOMPI.

Fig. 7. MINI-SCOMPI robot

C. *REC steam generator track system*

The SCOMPI and MINI-SCOMPI base system tracks consist of an aluminum plate with a rack gear screwed down its center. Two heat-treated steel rods, 10 mm in diameter for the SCOMPI and 6 mm for the MINI-SCOMPI, are mounted on either side of the track and act as guide rails for the manipulator. There are threaded holes approximately every 30 cm in which threaded rods can be screwed. Usually, these rods are used to fasten the track to the work area. For steam generator inspections, this method of fastening was not feasible. Track installation had to be done by a single operator in a very short time. A new track system integrating the original MINI-SCOMPI base system track thus had to be designed.

The base system track dimensions and positions were first established. For each of the 3,542 tubes, a MINI-SCOMPI kinematic inspection simulation was performed using IGRIP and CATIA V5 programs. The purpose was to guarantee 100% tube accessibility and to check collision and robot joint values. The simulation showed that a 1.4-m track had to be placed 10 cm above the tube sheet to be able to perform the inspection with the MINI-SCOMPI. Two track positions on the tube sheet were necessary to achieve a complete steam generator inspection.

Fig. 8. Kinematic IGRIP simulation of the REC inspection

Installation constraints were also determined: the track system had to be installable on the inlet side by a single operator in a ventilated suit, the single access point was the manhole, the operator had to stand upright and possibly hip high in the manhole, installation time had to minimized, the track system had to be rigid enough to ensure robot precision and the fastening system had to respect steam generator integrity.

The REC steam generator track system was developed based on all those parameters. The track system is 1.4 m long but to enter the bowl and to be easily manipulated by a single operator, it is divided into two 0.7-m sections each weighing 5 kg. To perform the inlet-side installation, the operator is actually hip high in the manhole. Each track section is fastened directly to the heat exchanger tube sheet by four newly designed expanding clamps.

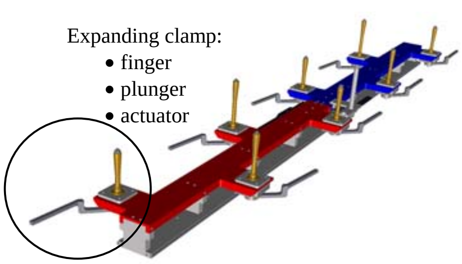

Fig. 9. REC steam generator track system – 2 sections

To install a section, all four expanding clamps must be inserted inside a steam generator tube. The operator then actuates the plunger of each clamp. In going down, the plunger opens finger wings and secures the system inside the tube.

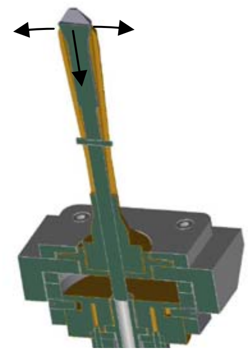

Fig. 10. Expanding clamp of the REC steam generator track system

Two track system locations on the tube sheet are necessary to achieve a complete steam generator inspection, which generally involves three jobs, averaging eight minutes each. The track system is first installed on its first location and about half of the tubes are accessible. The track system is then moved to its second location to complete the inspection. Lastly, the track system is retrieved. All three jobs are performed by a single operator.

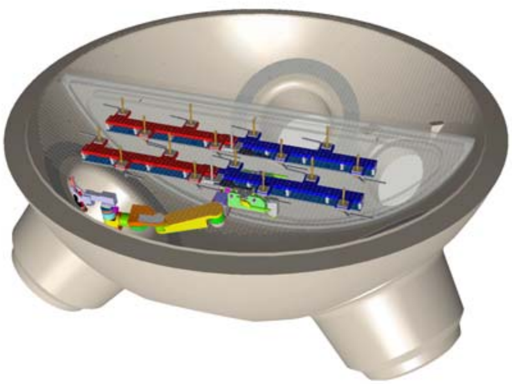

Fig. 11. REC steam generator track system locations

D. Automated probe-positioning sequence

One project objective was to integrate robot positioning into the G2 eddy current heat exchanger inspection system. That objective was achieved since the inspection sequence for a list of tubes is now fully automated. Probe positioning, probe displacement inside a tube and data acquisition are all achieved without human intervention.

The automated probe-positioning sequence is triggered by the TP program, which controls the probe push-pull device but which also acts as the eddy current chain manager, synchronizing all inspection tasks. The TP program sends the REC system the XY coordinates of the next tube to inspect, initiating the probe-positioning sequence. First, the robot moves the probe holder to this predefined tube.

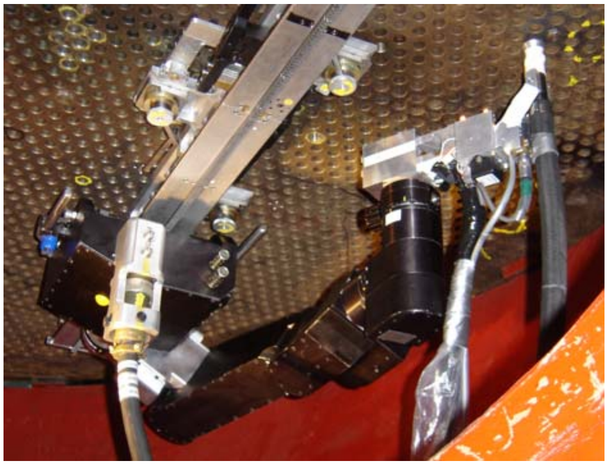

Fig. 12. REC robot, inside a steam generator mockup, moving into a tube

Next, the probe holder is adjusted horizontally and vertically with the help of the probe holder's tilt sensor. At this step, the XY position of the probe holder end guide must be corrected to achieve the required precision. The end guide is aligned with the tube using an IREQ-developed vision system with 0.5-mm precision. The probe can now be inserted into the tube to be inspected.

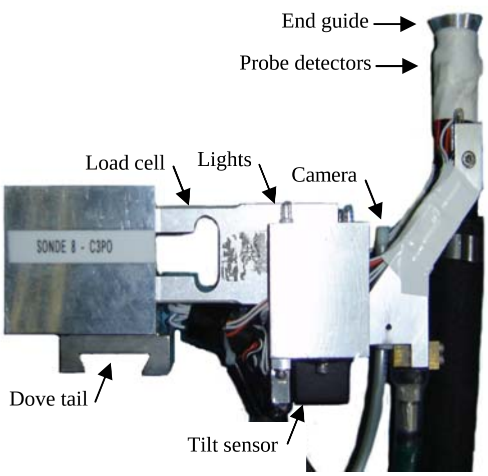

Fig. 13. REC probe holder for steam generator inspection

The REC system unlocks the TP program, which is ready to start probe displacement and data acquisition, and waits for the next positioning sequence. If required during probe displacement, the robot can apply force to the tube sheet with its integrated load cell, blowing air into the guide tube to help the probe move inside the tube.

E. REC vision system

As mentioned above, once in front of the desired tube, the position of the probe holder must be corrected to the required precision. This final alignment is performed by the REC vision machine using a camera on the probe holder, a computer twin to a frame grabber and application-specific image-processing software.

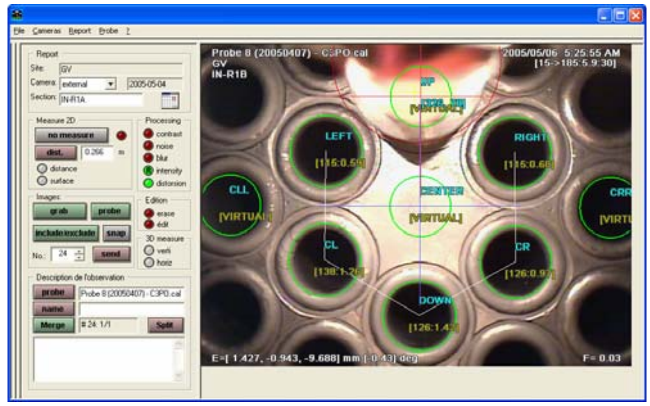

Fig. 14. REC vision system interface

The final alignment sequence is automatic. The vision system detects the tube and displays the results on live video. The borders of the detected tubes are shown as cyan circles. The XY coordinates of the detected tubes are displayed. The position correction is shown in the bottom left corner of the screen. The robot applies the correction. This sequence takes less than a second and repeats itself three to five times until the end guide is perfectly aligned. If this automated alignment fails, the operator can still manually align the probe holder using a reference schematic overlay with the live feed.

Fig. 15. Live video showing tube detection and identification

To perform tube detection, the image-processing software must first enhance the acquired images using such techniques as intensity equalization, lens distortion correction, noise suppression and blur reduction, to name but a few. Doing that enhances the definition and precision of tube contours. The image-processing software then suppresses such useless areas as the probe guide tube and colored or over-illuminated areas.

The software next applies a multi-threshold technique to detect elliptical contours. This technique uses a specific threshold for each contour instead of trying to figure out the right threshold for the whole image. Basically, the program selects the threshold that produces the best circles. The multi-threshold technique is simple, efficient, robust and very accurate. Figure 16 shows contour variants for different threshold values.

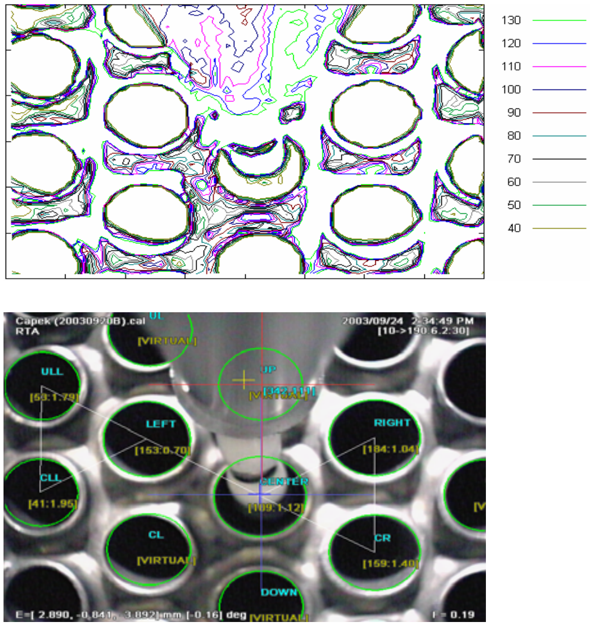

Fig. 16. Multi-threshold tube contour selection

After tube detection, the image-processing software uses a network algorithm to build a tube net. The tube net is primary based on detected tubes. The network algorithm also enhances the tube net by adding virtual tubes and eliminating invalid ones. Doing so increases overall precision.

Figure 17 shows 11 detected tubes with thresholds ranging from 41 to 122 in intensity and 4 virtual tubes bordering the tube net. Notice that one of the virtual tubes is actually the tube being inspected, labeled "UP".

Lastly, the resulting tube net is compared to the tube net model which gives the corrections for position and orientation of the probe holder relative to the tube being inspected. This information is sent to the robot, which applies the corrections.

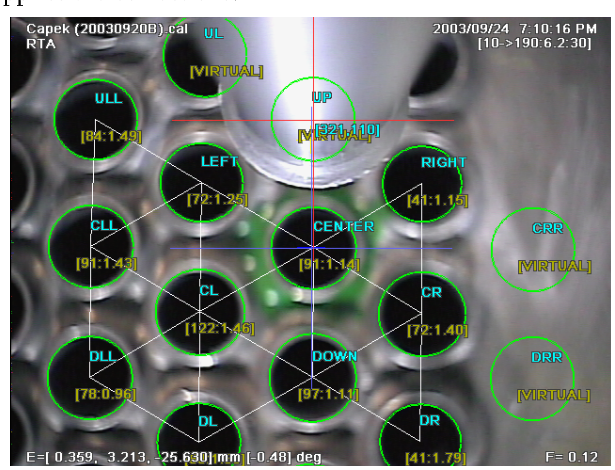

Fig. 17. Tube net bordering the tube being inspected

IV. PERFORMANCE AND FUTURE WORK

The 2005 steam generator inspection program used the REC system as the automated probe-positioning system integrated into the G2 inspection system and was a great success. The REC system, deploying the MINI-SCOMPI robot, was used to inspect two steam generators, SG1 and SG2. Both the REC track system and REC robot were successfully set up by a single operator. Three jobs were performed on each steam generator: track installation, track repositioning and track removal. The average job lasted about eight minutes. A check showed that all inlet-side tubes were accessible though, as planned, only half were inspected. A total of 1,892 tubes on SG1 and 1,771 on SG2 were inspected. Inspection of each steam generator lasted 96 hours. Automated positioning was successful. No failures or lost time occurred during the inspection.

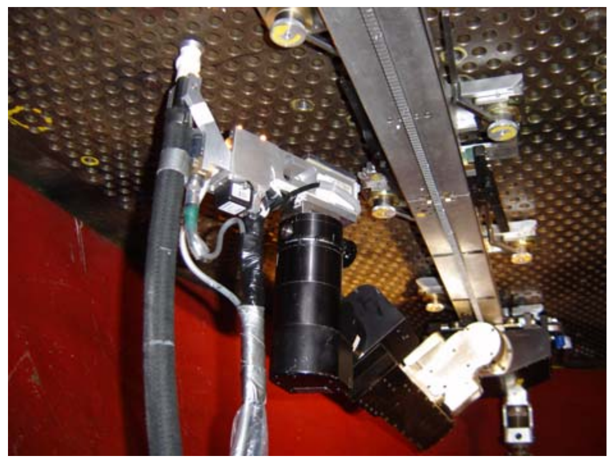

Fig. 18. MINI-SCOMPI setup inside the G2 steam generator mockup

This inspection program, conducted with the REC system deploying the MINI-SCOMPI robot, followed successful inspections in 2003 with the REC system deploying the SCOMPI robot. A moderator heat exchanger and a shut-down cooler heat exchanger were inspected. During those inspections, both automated probe positioning and onsite setup were also a success with no failures or lost time. In 2003, SCOMPI was used as the REC robot because the two heat exchangers had no dividing plate and a removable bowl. Both the robot and operators had both more space to work. A total of 3,845 tubes on the moderator heat exchanger were inspected in 96 hours. That number is higher than for the steam generator inspection since steam generator tubes are longer than moderator heat exchanger tubes. Furthermore, the moderator inspection was entirely performed with the same track location.

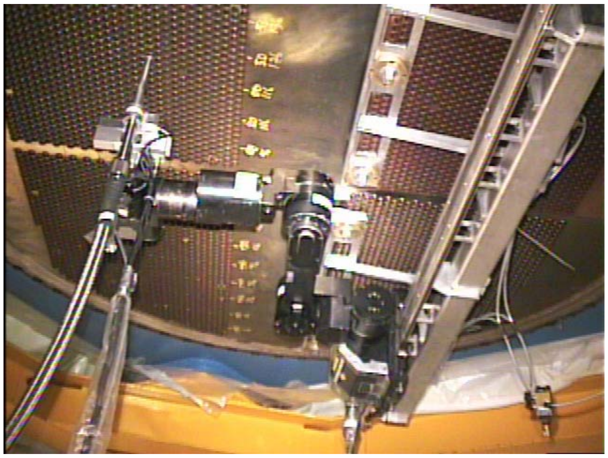

Fig. 19. REC system deploying the SCOMPI robot during the 2003 moderator heat exchanger inspection

The shut-down cooler heat exchanger inspection was shorter, lasting 24 hours for a total of 347 tubes inspected.

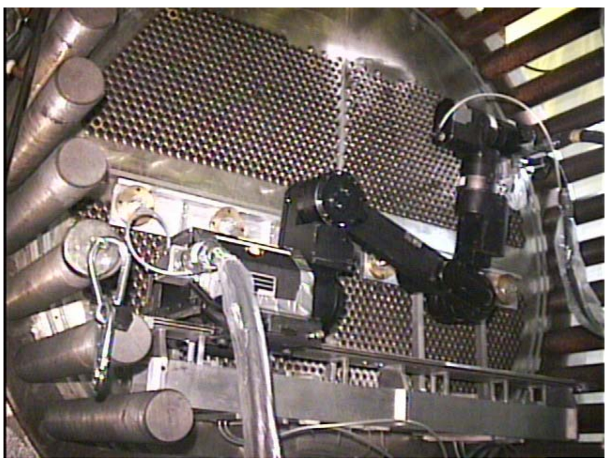

Fig. 20. REC system deploying the SCOMPI robot during the 2003 shut-down cooler heat exchanger inspection

Though REC system efficiency and reliability have been proven by the 2003 and 2005 inspections, further improvements are expected.

First, there are specific improvements for the steam generator inspection. Due to the manhole location, dividing plate orientation, and amount of magnetite, a new track system and a new probe holder must be designed to perform an inspection from the outlet side. Work on these improvements is ongoing even though G2 has always performed inspections from the inlet side.

System flexibility must also be improved. In the future, all heat exchanger inspections with the REC system will be performed using the MINI-SCOMPI. Before inspecting a new kind of heat exchanger, the REC system must be configured: 3D kinematic inspection simulation, new track system (if required) and new probe holder (if required). A track system and a probe holder both adaptable to the entire G2 heat exchanger family must be developed to avoid any design work before inspecting a new kind of exchanger. Tools to reduce the duration of 3D kinematic inspection simulation should also be developed. The duration now ranges from 35 to 70 hours.

Lastly, the user interface and file management have already been improved by changing from the IRMX to QNX operating system.

V. Conclusion

In 2002, Hydro-Québec's Gentilly-2 Nuclear Power Plant commissioned the Hydro-Québec Research Institute to integrate its SCOMPI technology into its eddy current heat exchanger inspection system. Renamed the "REC system", the integrated SCOMPI and MINI-SCOMPI robots have been used successfully to inspect moderator, shut-down cooler and steam generator heat exchangers. This success is based on close collaboration and a good working relationship between G2 and IREQ. All inspection system components have been designed or tuned to optimize inspection time, quality and cost. If new needs are identified, modification of those components would not be a problem. Specifically, the REC system could be easily integrated into a new heat exchanger inspection system. However, possible improvements have already been identified, essentially to reduce the time required to configure the REC system for a new kind of exchanger.

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