

June 18 - 21, 2012 - Toronto, Ontario

Remote Robotic Inspection of Irregular Surfaces on the Inner Diameter of the AECL NRU Reactor

Brent ZELLER¹, Luciano LOMBARDI², Philippe CYR¹, H. Douglas MAIR², Robert GINZEL¹

¹ Eclipse Scientific Ltd.; Waterloo, ON, Canada; Phone: +1 519 886-6717, Fax +1 519 886-1102;
e-mail: bzeller@eclipsescientific.com, pcyr@eclipsescientific.com, rginzel@eclipsescientific.com

² Utex Scientific Instruments; Mississauga, ON, Canada; e-mail: llombardi@utex.com, dmair@utex.com

Abstract

In May of 2009, the NRU (National Research Universal) reactor was forced to shut down after a small heavy water leak. In 2009-2010 repairs were performed in order to restart medical isotope production mid-August 2010. Since the NRU vessel's return to service, a series of periodic inspections is required to ensure the safe operation of the reactor. Eclipse Scientific in collaboration with Utex Scientific Instruments and Liburdi Automation developed the NDE inspection system for the In-Service Inspection program of the NRU vessel.

In addition to the difficult environmental, delivery and inspection circumstances the inspection team was faced with the problem of doing an immersion inspection of the inside surface of the reactor vessel through a small 120 mm access port at a distance of more than 10 m to the inspection area at the bottom of the reactor. The vessel was built over 50 years ago and as the inner surface was modified by the repair program during the forced outage, there were no accurate drawings of the inner surface of the vessel that an automated system could rely upon. Eclipse Scientific in collaboration with Liburdi Automation developed a robotic arm designed to enter from the remote access port to deploy the Phased Array and Eddy Current Array inspection heads into the reactor vessel. The motion control and data acquisition system was developed in collaboration with Utex Scientific Instruments using their InspectionWare software.

This paper will highlight the challenges faced in the development of an inspection system capable of using ultrasonic signals to learn a surface and, using this acquired surface topography, effectively and safely deploy and articulate the different inspection heads required to perform the In-Service Inspection of the NRU vessel.

Keywords: complex inspection, phased array, ultrasound, eddy current array, automated inspection, motion control

1. Introduction

On May 15, 2009 a heavy water leak was discovered in the National Research Universal (NRU) nuclear reactor vessel at the Atomic Energy of Canada Limited's (AECL's) Chalk River Laboratories facility. The leak was attributed to a small hole in the reactor vessel wall caused by corrosion and a thorough non-destructive examination (NDE) of the calandria (reactor vessel) found additional areas of wall thinning and localized pitting. Ten repair sites were identified and the chosen method of repair was to increase the thickness of the wall from the vessel inside diameter (ID) using a variety of techniques involving weld build-up. The repairs were completed and inspected and the NRU reactor was returned to service on August 17, 2010. The facility was restarted with the provision that in-service inspections (ISI) of the reactor vessel be conducted annually to monitor for further corrosion and assess the repair welds[1].

The team contracted to perform these inspections consisted of Eclipse Scientific Inc. (Waterloo, Ontario, Canada), Liburdi Automation (Stoney Creek, Ontario, Canada) and Utex Scientific Ltd. (Mississauga, Ontario, Canada). A unique robotic inspection system was designed and built to

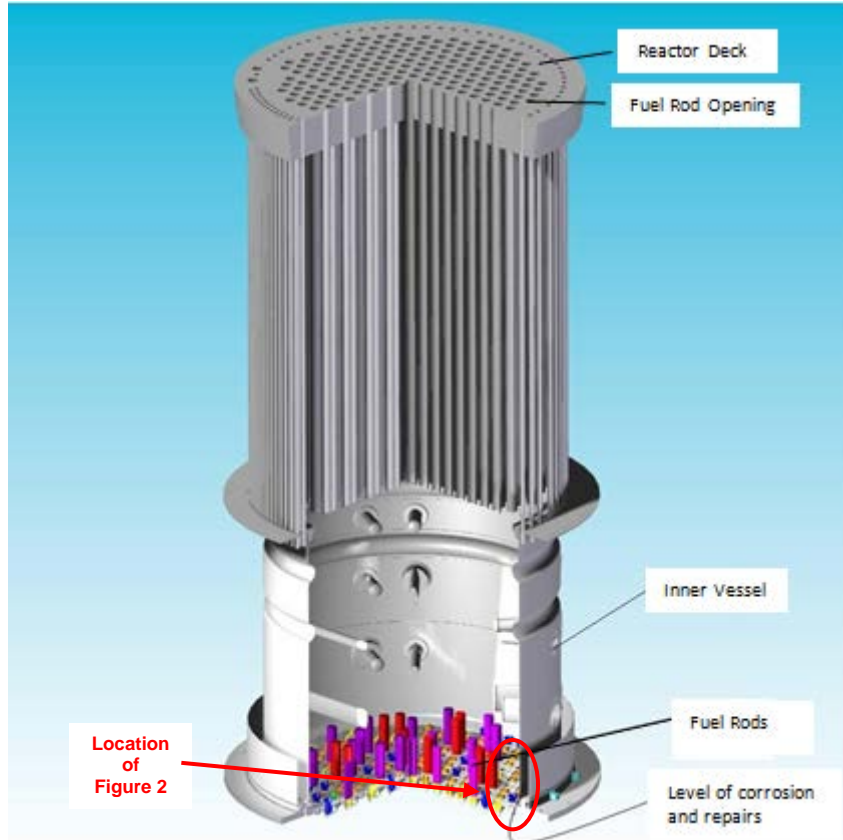


Figure 1. Cutaway view of NRU reactor

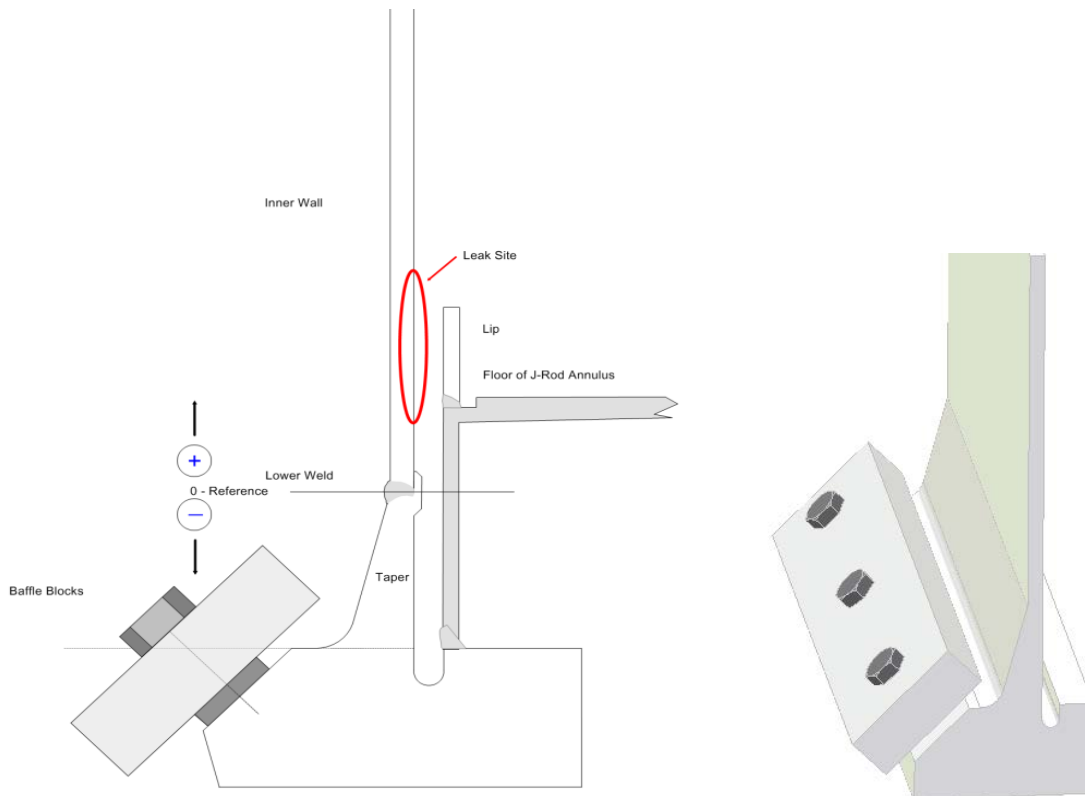


Figure 2. Cross section of reactor wall at the bottom in the region of the corrosion

perform NDT inspections for signs of corrosion, cracks, and metal loss from inside the reactor vessel while it is fueled and filled with heavy water. In addition to the difficult environment there were very restrictive access issues to overcome. The robot was fully automated and positioned the NDT instruments by controlling them through 6 axes of motion. The problem of precisely positioning the instruments to scan over an irregular inside surface was overcome by having the control system learn the contour it needed to follow. The tool and control system development is described in this paper.

2. Scope of In Service Inspection (ISI)

The Canadian Nuclear Safety Commission (CNSC) license of the NRU depends on completing the ISI according to the inspection specifications. These inspections are discussed below.

2.1 NRU Calandria

The NRU calandria is approximately 11 m in circumference and is filled with the fuel rods and heavy water during the ISI (Figure 1). The location of the leak and other corroded areas was at the very bottom of the vessel wall as shown in Figures 1 and 2[2].

The reactor vessel is obviously a very difficult environment with high radiation fields and radioactive materials which contaminate any equipment used. In addition to this, access to the calandria is very restricted. The only point of entry for the inspection equipment is through existing 120 mm diameter fuel rod openings in the reactor deck at the top of the 9 m tall reactor structure (Figure 1).

A number of inspections are required. The only inspection required on the bare calandria wall is wall thickness measurement and monitoring with baseline and follow-up inspections at specified intervals in order to monitor for any continuing wall loss. There is a variety of welded repair types: some repair sites consist simply of layers of weld on the calandria ID; some sites include small plates which were tacked to the calandria ID and then welded over; finally some sites include small structural plates which were fully welded to the calandria ID. The inspections required on or around the repair sites are described in Section 3.

It should be noted that the calandria has already seen nearly forty years of service. In addition to any changes in the basic cylindrical shape over those years, the welded repairs stressed the vessel and caused some additional warping of the walls. The weld build-up deposited on the ID can be 5 or 6 mm thick and has been left in its rough-surfaced as-welded state. All of these factors contribute to the irregularity of the ID surface of the calandria.

3. Inspection Procedures

A combination of ultrasonic (UT) and eddy current (ET) techniques was used to meet the inspection requirements. Each technique has its own tolerances for positioning of the NDT probes and the tool and control system needed to be able to meet all of them.

3.1 Delivery Tool and Motion Control System

The delivery tool consists of a long tube which fits through the fuel rod opening and reaches to the bottom of the calandria (Figure 3). A robotic arm with a specially designed fixture at the end extends from the tube as seen in Figure 3. The robot was fully automated and positioned the NDT instruments by controlling them through 6 axes of motion. The six axes are:

1. Rotation of the entire tool (R axis)
2. Moving the entire arm assembly up or down (Z axis)
3. Changing the angle of the arm (Elbow axis)
4. Extending or retracting the arm (E axis)
5. Changing the pitch of the end of the arm (Pitch axis)
6. Changing the yaw of the end of the arm (Yaw axis)

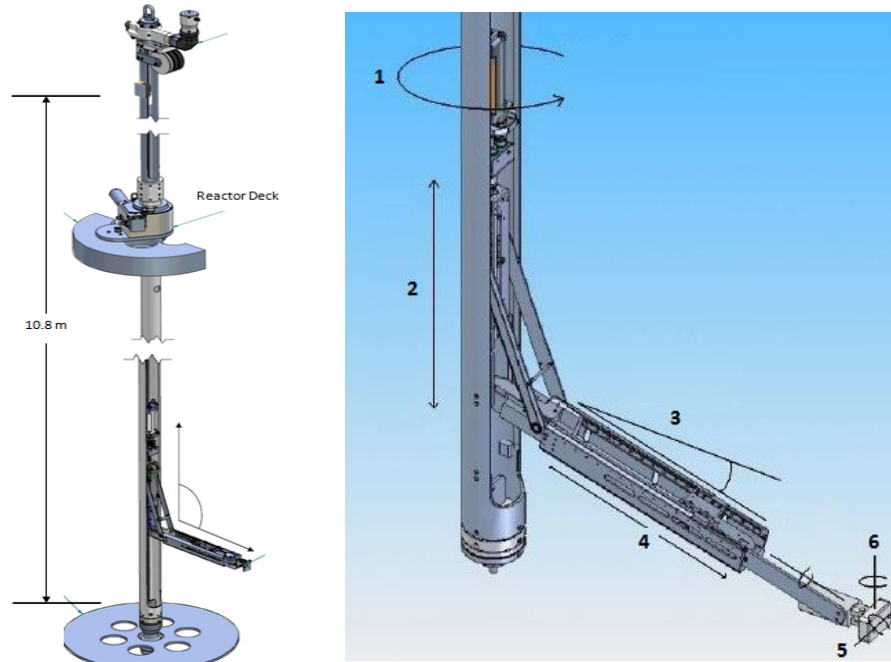


Figure 3. View of Delivery Tool and of Robotic Arm Extended

The motion control and data acquisition system was created using InspectionWare which is an NDT software system for data acquisition and motion control developed by Utex Scientific Inc. The motion control and data acquisition system for the ISI is extremely complex and involved the development of numerous modules for controlling the tool through various calibration and data acquisition procedures.

There are a total of five different inspection heads (also known as end effectors) which fit onto the end of the arm in order to complete all the required inspections. There are two UT heads and three ET heads which are used for a total of seven different inspection techniques. These techniques are discussed in more detail below.

3.2 Ultrasonic Techniques

All UT inspection techniques are immersion using the heavy water as couplant. That is, the probe produces the sound which travels through the heavy water which fills the vessel to the ID surface. The angle of the sound in the vessel wall is determined by the angle of incidence on the surface and Snell's law of refraction.

The first UT inspection head holds two phased array probes and can be tilted at controlled angles to produce shear waves when required. The larger probe is used for all Wall Thickness (WT) inspections and for examining the Heat Affected Zone (HAZ) around the sides and along the top of the repair welds. The smaller probe is used to inspect the welds holding the structural repair plates. The second UT head holds another larger phased array probe protected by 'bumpers' to scan the HAZ along the bottom of repair welds. This requires the probe to move between the

baffle block and wall (Figure 2) scanning upward with shear waves. There were four UT techniques used in the inspection. The accuracy of angular positioning required was ± 1 degree. The accuracy of translational positioning varied depending on the axis and on the technique being used but in some cases the probe needed to be positioned within ± 3 mm of the edge of a weld or plate. It is also worth noting that the positioning for data collection must be repeatable both in successive scans during the same inspection and also for scans performed during different inspections. If any indications are found their position must be recorded with considerable accuracy in order to locate them for future reference.

3.2.1 Wall Thickness Inspection

The larger phased array probe uses one group configured as a 0 degree compression wave linear scan for inspection over bare wall and over weld repair build-up. It covers about 30 mm of the inspected area with each pass. The probe surface must be held normal to the ID surface of the calandria at all times and the axial and circumferential positioning must be recorded as accurately as possible. Figure 4 shows the delivery tool with the first UT head mounted on the robotic arm while performing WT scans in one of the mock-up facilities.

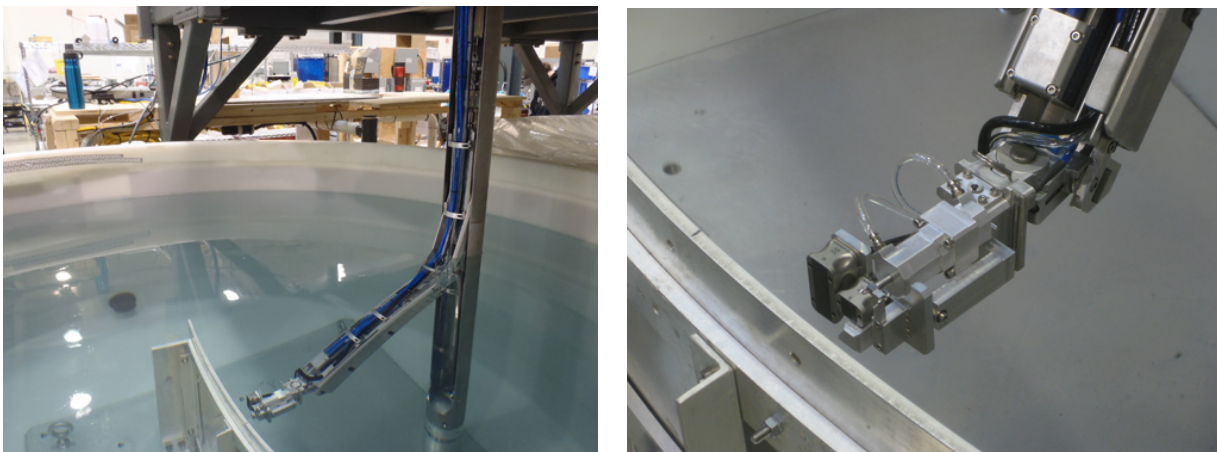


Figure 4. Photo and detail of delivery tool and robotic arm with UT end effector in mock-up

3.2.2 HAZ Inspection

The larger phased array probe is configured with two groups. Each is a shear wave sectorial scan with one group near to the repair weld edge and one away from the weld edge. The HAZ around the weld on the vessel inside diameter (ID) and outside diameter (OD) are both covered with this technique. The data is collected in a single line scan along the edge of the weld. For this technique the angular positioning and the translational positioning in all axes are very important to obtaining data. Note that there is insufficient access along the bottom edges of some welds for this technique. In those circumstances the other UT head must be used (Section 3.2.3).

3.2.3 Lower HAZ Inspection

This technique is performed as a single line scan along the bottom of repair weld sites. Note that it only covers the OD of the calandria. It is a larger probe with two groups but these are shear wave linear scans. One group is designed to refract from tapered surface below the calandria wall to the area of interest and the other group is designed to refract from the surface of the flat wall (in the sites where a small region of flat wall exists below the weld and above the taper). The angular positioning and all axes of translational positioning are important to obtaining data.

3.2.4 Edge of Plate Inspection

This technique is performed to meet the requirements for inspection of the structural plate welds and is performed as a single line scan along each edge of a repair plate. The smaller probe is used with a single group configured as a shear wave sectorial scan. This is a volumetric inspection of the plate edge weld. As with the other shear wave scans the angular and translational positioning are important to obtaining data.

3.3 Eddy Current Techniques

All ET inspection techniques require contact between the probe and the vessel surface with no lift-off. That is, the probe face must remain in contact with the inspected surface for good data. Lift-off of more than 2 mm from the surface means that no useful data will be obtained.

The first ET inspection head is designed to detect thinning of the calandria wall (not over weld repair) to less than 3.5 mm. The second ET head holds a transmit/receive probe designed to detect cracks in the surface of the weld repair. The third ET head holds a transmit/receive probe designed to detect cracks in the ID surface of the calandria in the HAZ around weld repairs. These probes must be held flat against the irregular surface on the inside of a cylinder in order to obtain data. The third head has a much smaller surface area but it must still be held flat against the calandria wall in order to obtain good data.

3.3.1 Hi-Res Wall Thickness Inspection (sub 3.5 mm)

The high resolution WT head with a surface area of approximately 680 mm² covers about 30 mm with each pass but the successive scans overlap to ensure proper coverage of the inspected area.

3.3.2 Weld Crown Inspection

The Weld Crown head with a surface area of approximately 550 mm² covers about 30 mm with each pass but the successive scans overlap to ensure proper coverage of the inspected area.

3.3.3 HAZ (ID) Inspection

The HAZ inspection head is rastered over the inspected area in 0.5 mm index increments.

4. Complex Motion Control

This inspection poses many great challenges for motion control. The robot arm and end effector are very complex components. Also complicating this inspection is the requirement to collect many types of data (UT WT, UT HAZ, ET HAZ, etc.) using different types of probes. In addition, the calandria wall is now a complex surface due to repair welds and warping during the weld process. All these factors conspire to create a difficult inspection that requires complex solutions for motion control. Contour following along with the use of inverse kinematics to control the robot has made this inspection possible.

The following sections will describe in greater detail the simulated robot, simulated calandria and various techniques used to handle complex motion.

4.1 Simulation of the Robot

The robot used in this inspection is a 6-axis system as described in section 3.1. In addition to the 6 axes, the end effector provides a greater range of motion and added complexity. The entire tool is simulated in InspectionWare in order to support the ability to perform inverse kinematic

calculations (Section 4.3). Figure 5 shows the simulated robot in InspectionWare and the motion axis tree where specific motion parameters, as well as axis position and dimension, are input.

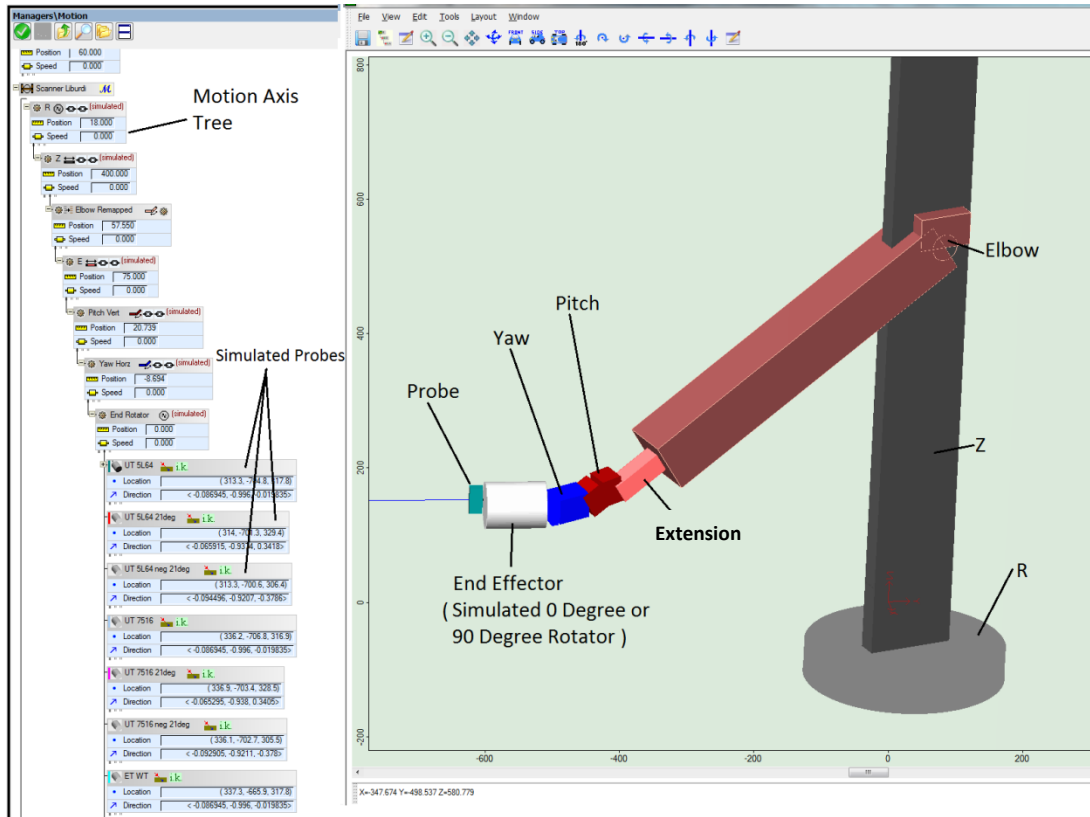


Figure 5. Simulated robot and motion axes

The end effector that connects a specific probe to the robot has two manually-controlled degrees of freedom. First, the end effector can be rotated 90 degrees, and secondly, it can be tilted ± 21 degrees. In InspectionWare the 90 degree rotation is simulated by a rotation axis joining the Yaw axis to a particular probe (Figure 5). In order to handle the various inspection probes and the ± 21 degree tilting of the probes, an array of probes has been simulated.

4.2 Simulation of the Calandria

A simulation of the calandria is used to locate the robot during inspection. This allows for mapping surface points which can be used as scanning coordinates that relate to real physical positions within the calandria (circumferential position). To locate the robot in InspectionWare, coordinates of a deployment position as well as the zero-degree direction of the robot relative to the zero of the calandria are input into InspectionWare (Figure 6). Locating the robot in simulation is useful for two reasons. First, knowledge of the robot relative to the vessel wall can aid in ensuring safe deployment and movement of the robot. Secondly, if accurate positioning is acquired, positional data of scans in specific calandria regions can be compared year-to-year.

4.3 Inverse Kinematics and Complex Surfaces

Inverse kinematics is a branch of classical mechanics whereby one attempts to determine the position (displacement axis) or angle (rotating axis) for of all axes in order to place an end

effecter, a probe in our case, to a specified position and direction. The forward kinematic problem is much easier to solve. In the forward problem one defines positions or angles for each axis of the robot and calculates where the probe will be. In the forward kinematic problem, position and direction of the end effector is a function of all axes positions and angles. In the inverse kinematics problem, one specifies the position and direction of the end effector (center of probe face in our case). Then one must determine the position or angle of each axis to place the end effector in the correct orientation. In general, there is more than one possible solution for this problem and analytical solutions are often difficult to achieve. In InspectionWare an iterative relaxation-type solution has been implemented. One would like to orient a probe a specified distance from the calandria wall, as well as a specific angle relative to the wall.

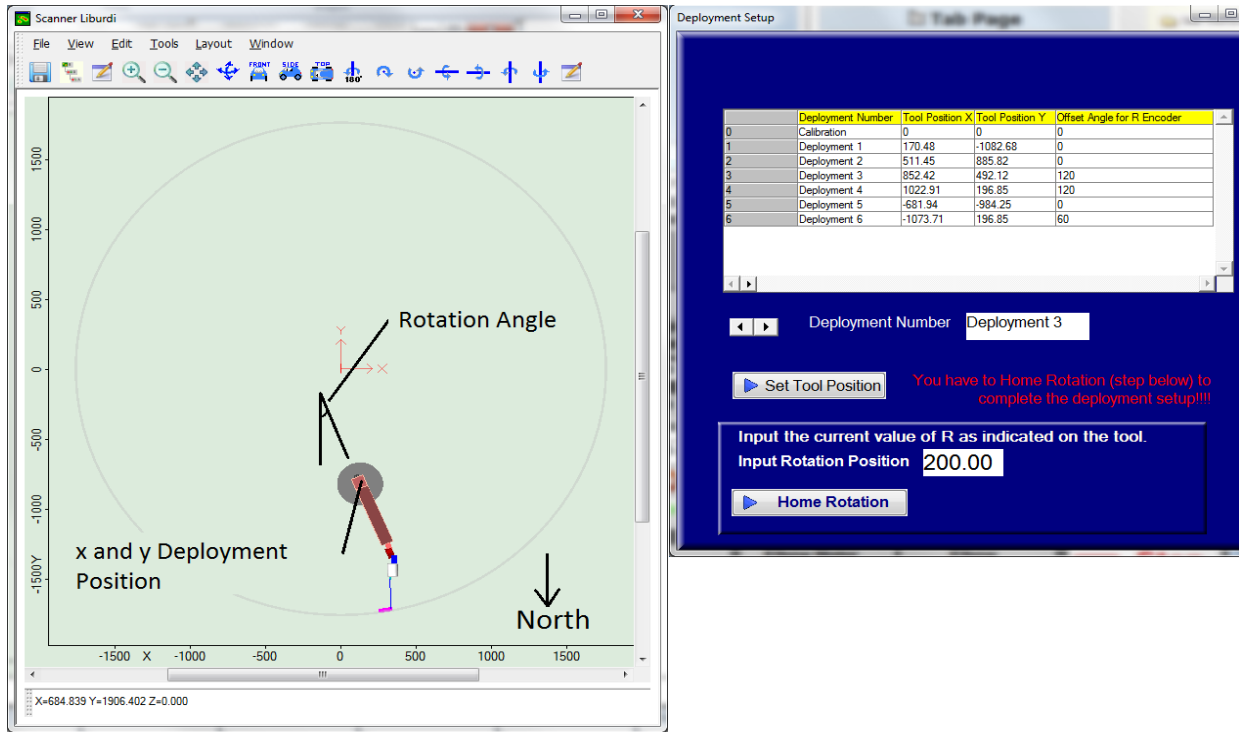
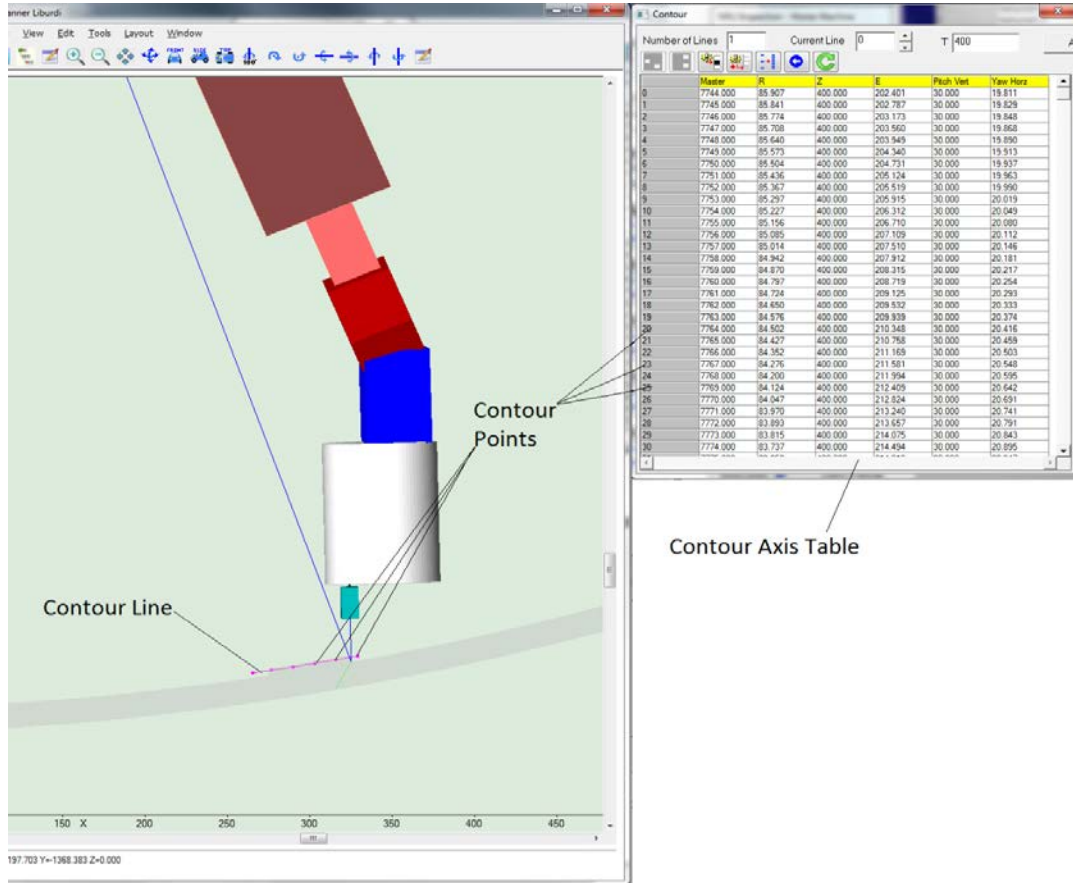


Figure 6. Simulation of calandria and deployment positions

The general scheme implemented is as follows: first rotate R such that the probe direction roughly points in the desired direction. Due to the geometry of the calandria and the choice of axes that make up the robot, the angle of the probe relative to the longitudinal direction (Z axis direction) is completely determined by the pitch angle (the elbow angle is held fixed at one angle in a single deployment). Then, the iterative relaxation method is performed by comparing the current probe direction and position to the desired position and direction. The difference in magnitude and angle is calculated and used to adjust the values of the following axes, the rotation axis R, the extension axis E, the Z axis and finally the Yaw axis. This process is repeated until corrections to all axes are smaller than a specified motion tolerance for each axis. All these calculations are performed within the simulator and thus, it is imperative that the robot be properly simulated and properly homed so that the simulation positions and the real robot positions correspond to each other. The iterative solution for the inverse problem has been described; however, it is not in general clear how one can specify where one would like to orient the probe within the calandria. This is due to the fact that one cannot accurately simulate the calandria since it is not a perfect cylinder nor are the deployment positions known to sufficient

accuracy. A clever technique has been devised to circumvent this issue by using the UT wall thickness probe as an effective sensor to orient the robot within the calandria. The UT wall thickness probe is used to create a topographic map (2D TOF scan) that gives information about the surface of the wall. This topographic information, along with the knowledge of the robot axes positions used during the acquisition (contour points) of the 2D wall map is used to create a surface-normal map of the calandria. This surface-normal map is created by using the TOF data and the probe position and direction at each scan point. The surface-normal map, along with the inverse kinematic solution described above can be used to position the probe at a desired stand-off distance as well as specific angles relative to the calandria wall.



4.4.2 Contour Lines Calculated from TOF Data and Inverse Kinematics

Once a 2D contour has been obtained as described in 4.4.1 it is used to acquire TOF data of the calandria. This TOF data is used both for wall thickness analysis of the calandria as well as a 2D topographic map required for inverse kinematic calculations. Scans such as HAZ, LHAZ, LOF are all 1D scans that require accurate positioning both in stand-off distance as well as a proper entry angle relative to the wall. Figure 8 shows an example of TOF data acquired. This data set has been acquired with a 2D contour and thus, information of all relevant axes is stored. The position of these axes can be used to infer the position of the probe at all points in the scan. In order to produce a 1D contour using inverse kinematics an annotation is used (Figure 8) as a positioning reference to mark where one would like to calculate a new set of contour points. The points on the annotation are contour points that represent the desired physical position the probe will be moved to during a scan. The 2D TOF scan and contour axes used in the scan completely define all necessary information required to obtain a surface-normal map of the calandria as well as perform inverse kinematic calculations.

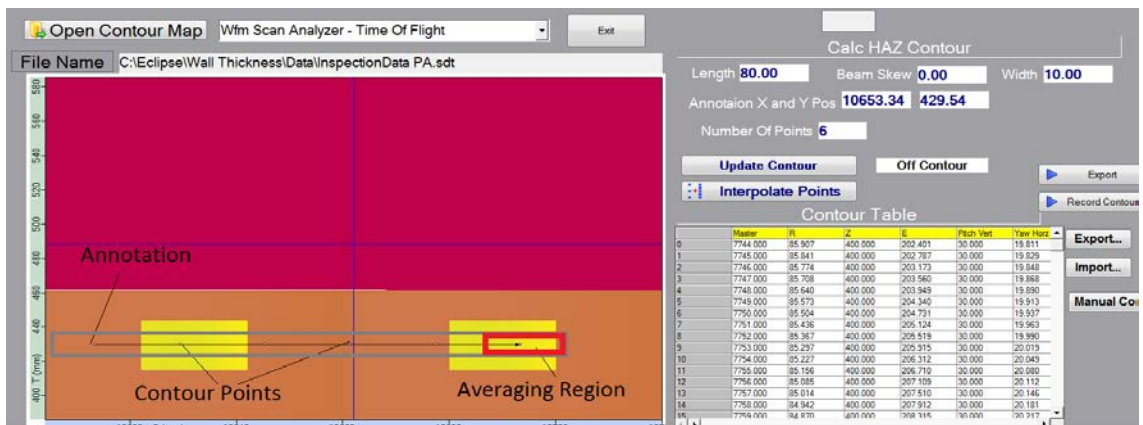


Figure 8. TOF data and annotation used to obtain 1D scans calculated using inverse kinematics

6. Conclusions

The environmental and access problems could only be overcome with remote inspection. Manually operated tools expose operators to radiation and possible contamination. The necessity for millimetre accuracy in positioning the UT and ET heads on an irregular surface required more than a simple geometric model. The ability to learn the surface contour and, through reverse kinematics, control the inspection heads with the necessary accuracy was the only way this inspection could be completed. The ability to learn and position inspection heads in this manner has endless applications. The flexibility of InspectionWare by Utex and the delivery tool design by Liburdi allowed the team led by Eclipse to successfully complete the NRU inspection.

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