



COOP-CT-2004-512984

RIMINI

**Development of New and Novel Low Cost Robot Inspection
Methods for In-Service Inspection of Nuclear Installations**

Horizontal Research Activities Involving SMEs

Co-operative Research (CRAFT)

Publishable Final Activity Report

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Project co-ordinator organisation: TWI Ltd

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1 Project execution

1.1 Project objectives

The strategic objectives of this project were:

- 1 To significantly reduce the cost of inspection of nuclear reactor pressure vessels by reducing the time for inspection.
- 2 Improved safety through higher reliability and repeatability of the inspections.

The following NDT methods and equipment were developed.

- MicroPulse 5PA - 128 channel phased array instrument. Later proofed and enabled for full matrix capture. The instrument complete with its own driving and display software. Produced by Peak NDT.
- SimulUS - conventional and phased array ultrasonic beam modelling software. The software has been validated by TWI against two other models and physical trials.
- ACFM system - calibrated on implanted defects and verified on real and artificial stress corrosion cracking. Produced by TSC.
- Multichannel, eddy current array, validated on SCC. Designed and tested by TWI Ltd.
- Phased array TRL probe with 2 x 64 element immersion array. Concept designed by TWI. Detail design and manufacture by Vernon.
- Wall climbing robot designed and manufactured by South Bank University. Designed and manufactured to work aside a PWR with nuclear compatible materials and control system.
- Robot arm for scanning inside surface of nozzles after deployment from climbing robot.

1.2 List of contractors

TWI Ltd – Project co-ordinator (UK)
ATG (Czech Republic)
CEZ (Czech Republic)
Ignalina NPP (Lithuania)
LSBU (UK)
Mitsui Babcock (UK)
NNC (UK)
Peak-NDT (UK)
Reaktor (Slovakia)
Tecnitest (Spain)
Trueflaw (Finland)
TSC (UK)
TVO (Finland)
Vernon S.A. (France)
Zenon (Greece)

1.3 Work performed

1.3.1 Ultrasonic phased array probe specification

A 2.5 MHz transmit-receive longitudinal phased array (TRLPA) probe was selected with two 64 channel arrays the transmitter and receiver system. The design was optimised using the Peak-NDT SimulUS modelling package and the specification was as follows:

Roof Angle 3.1°, Scan axis 4 elements with 3mm pitch, Index axis 16 elements with 2mm pitch. This probe was manufactured by Vernon and is shown in Figure 1 below.

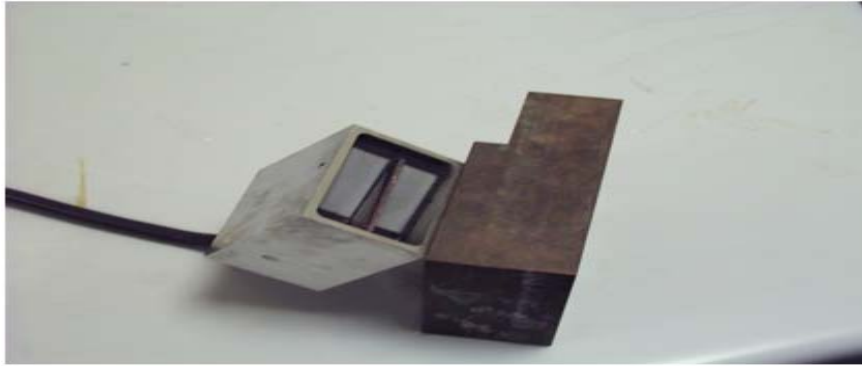


Figure 1 TRPLA probe.

1.3.2 Validation of SimulUS

The theoretical ultrasonic beam model SimulUS developed by Peak NDT was validated during the course of the RIMINI project. SimulUS was then used to model and optimise the Transmit-Receive Longitudinal (TRL) phased array probe.

SimulUS was validated using evidence from experimental data collected at TWI and from past validation programmes. SimulUS is primarily a continuous wave model designed to run fast and allow on site personnel to verify their inspection strategy.

The validation programme for SimulUS involved previously well characterised single crystals and linear phased array probes. In conclusion, SimulUS was validated and showed good agreement to experiment and other models such as CIVA. SimulUS will provide a commercially powerful tool.

Figure 2 shows a typical example of a cross section of the sound field generated by a rectangular single crystal.

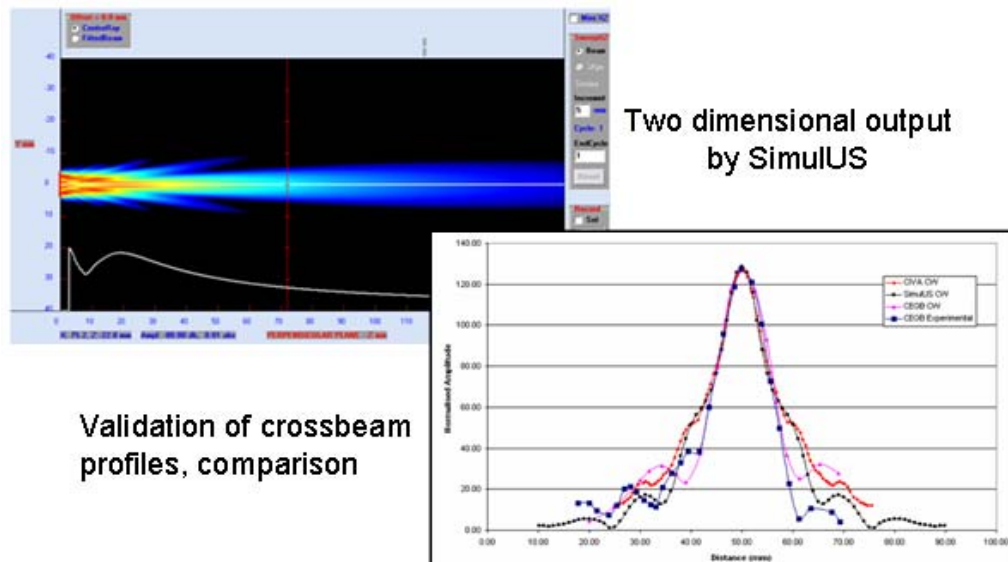


Figure 2 The two dimensional output of SimulUS and validation of profiles.

Performance evaluation of TRLPA probe.

Test blocks were obtained representative of the dissimilar metal joints that exist in Nuclear Power Plants (NPPs). The weld is a K-prep austenitic weld with a nickel buttering layer to the ferritic (508 Class 3) Reactor Pressure Vessel (RPV); the nozzle is made of 316LN stainless steel. Figure 3 below shows the general outline of test blocks A and B and the position of the side drilled holes, block A contains 6mm Side Drilled Holes (SDHs) and block B 3mm SDHs.

Test Blocks A and B have four SDHs on either side.

- SDHs 1 to 4 are on Side 1 along the nickel buttering layer interface (between the ferritic RPV and the weld metal);
- SDH 1 is near the back wall and SDH 4 is near the inspection surface.
- SDHs 5 to 8 are on Side 2 along the fusion line of the K-prep weld (between weld metal and the stainless steel nozzle);
- SDH 5 is near the back wall and SDH 8 is near the inspection surface.

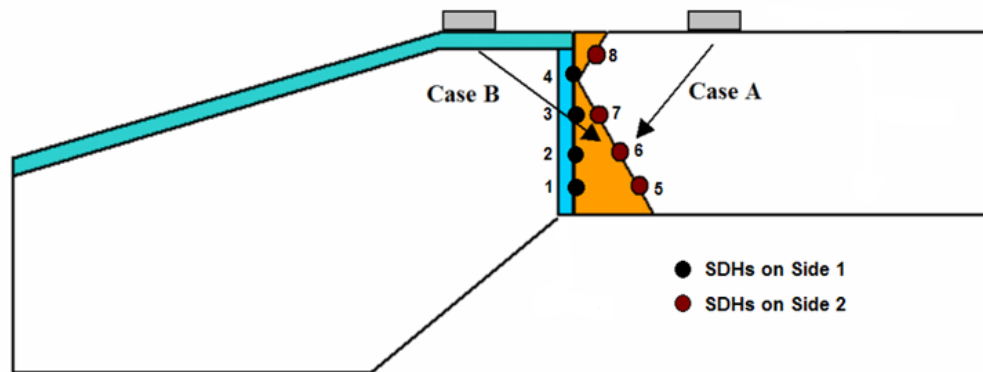


Figure 3 The two main approaches (Cases A and B) are shown along with the location of the holes in the two blocks.

The robotic delivery system approaches the weld from the Case B direction travelling from the RPV into the nozzle. However, by reconfiguring the orientation of the TRLPA probe, inspection from the Case A direction is made possible.

The development of the techniques took place in the laboratory in a suitable immersion tank with encoded motors to record the position of the probe with respect to the Test Blocks. Figure 4 below shows Test Block B immersed in the development tank with the scanning frame and probe holder. The Peak NDT MicroPulse 5PA is the instrument on the bench which was used to drive the probe and collect the data. The data can then be analysed on a computer using the ArrayGen software supplied by Peak NDT.



Figure 4 Laboratory set-up.

Typical results on Test block B in the form of sector scans are shown in Figures 5 and 6 below

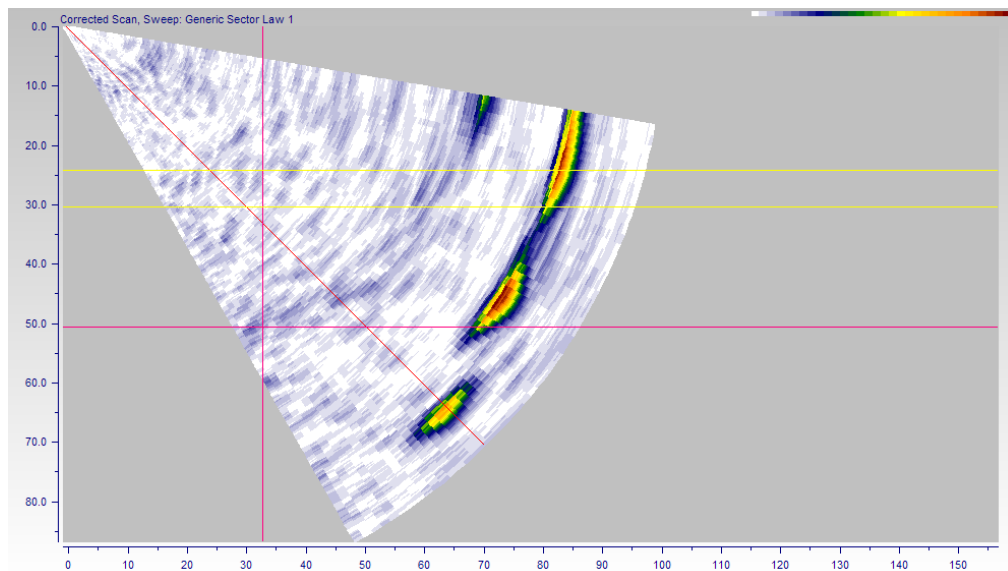


Figure 5 Case A - holes 3, 4, and 5.

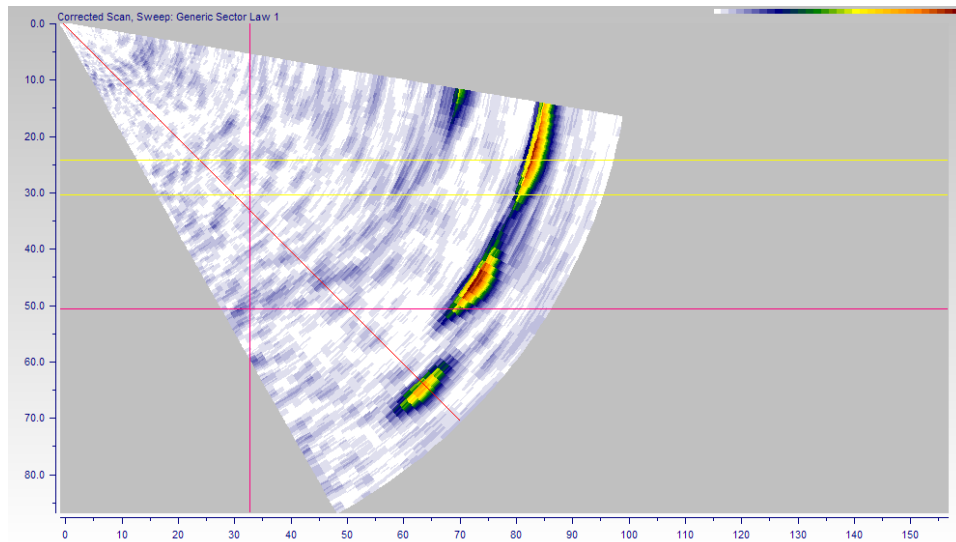


Figure 6 Case B - holes 1, 2 and 3

Overall it was concluded the TRLPA probe demonstrates better signal-to-noise performance when compared to single crystal probes. It is able to detect defects which lie along the weld-nozzle and weld-RPV fusion faces. Two configurations were studied and both proved viable for use in inspection.

The TRLPA was optimised for the detection of defects up to a depth of 60mm in the component. However experimental trials have shown that, even though the beam widths are increasing at greater ranges, the TRLPA probe is still capable of detecting defects to the full depth of the component (80mm).

1.3.3 Alternating current field measurement (ACFM)

ACFM probe specification and evaluation

Although an array probe is good for inspecting flat plates, it is much harder to inspect the doubly curved geometry around a reactor pressure nozzle. It is not possible to make a rigid array to fit the geometry without having excessive lift-off between sensors and metal surface. On the other hand, a flexible probe would be quite vulnerable to damage when deployed by robot, and difficult to seal against water ingress.

It was therefore decided that a non-array probe be used for the ACFM inspection. This is possible because the robot deployment system was designed to be able to scan such a probe in a well-controlled manner over the nozzle surface once it has docked.

To evaluate ACFM and EC probes a sample of stainless steel cut from the curved outer edge of a nozzle was supplied by Babcock. Surface flaws were introduced by True Flaw. Two known defect areas marked A and B are shown in Figure 7 below.

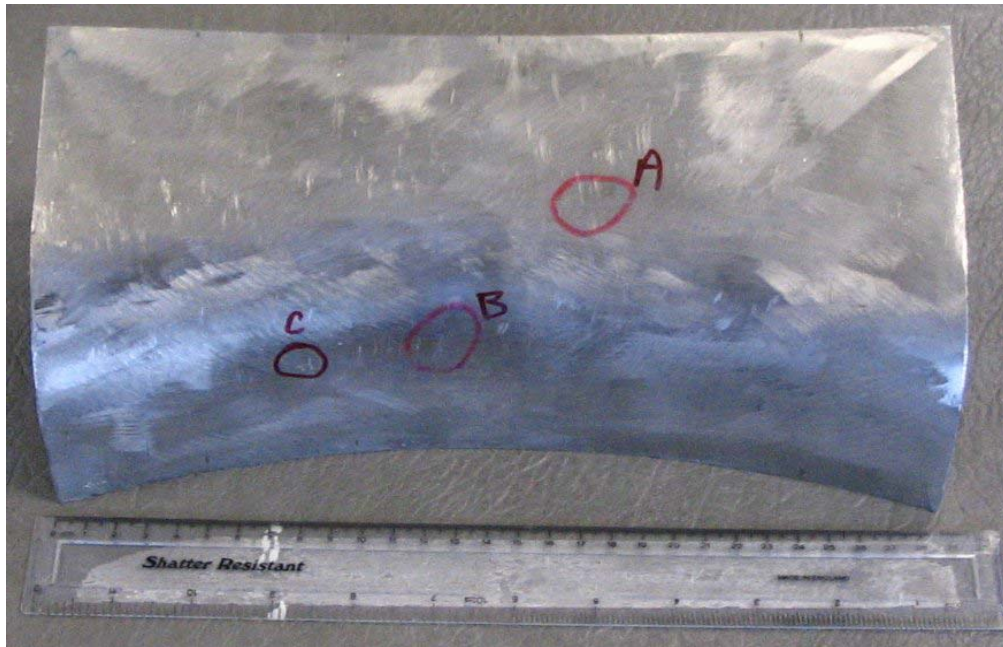


Figure 7 Outer curved section of RPV with introduced surface flaws.

ACFM scans were made of the sample using an existing ACFM array probe. Defects A and B were clearly detected, together with a third defect (marked C in Figure 5).

Defect B was quite interesting because it appeared on the surface as two cracks crossing each other, more or less at right angles. This means that, for the single uniform input current used in standard ACFM probes, one part of the defect will be at right angles to the current, giving a strong perturbation and strong ACFM signals. However, the other part of the defect will be parallel to the current, giving no perturbation.

In ferritic steel, a defect orientated parallel to the induced current often produces a measurable signal caused by the magnetic field lines jumping across the defect. However, the strength of this signal is determined more by the opening of the mouth of the defect than by the defect depth. Also, this effect is not present in non-magnetic metals like the 316 stainless steel used here.

In order to detect defects in any orientation in a non-magnetic metal, it is necessary to use two orthogonal input currents in the probe.

By using a twin field probe and hence three orthogonal sensor coils, the two orthogonal parts of the crack could be identified in the ACFM data. Therefore a special pencil-shaped probe was required containing twin inducing fields and a concentric triple sensor coil, as shown in Figure 8 below.

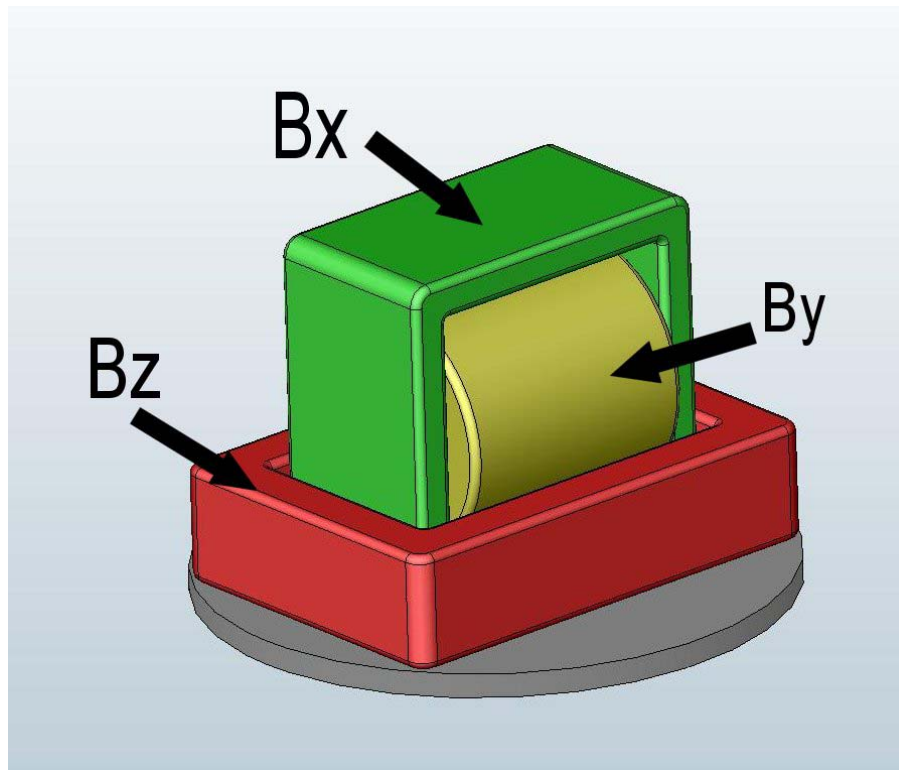


Figure 8 Triple ACFM sensor coil.

The design of the ACFM probe consists of a pencil-shaped housing containing the probe electronics, with a separate wedge-shaped nose containing the sensor coils. The sensors were a concentric triple-coil arrangement, in conjunction with twin orthogonal inducing fields. This allows defects in any orientation to be recognised and sized without having to rotate the probe and rescan.

1.3.4 Eddy current array probe

Design and evaluation

In order to scan a large area and thereby increase the coverage on each scan and reduce the inspection time an array probe is required. However, to cope with the doubly curved geometry of the reactor nozzle, a conformable (semi flexible) array is required. Several types of probe were evaluated.

The conclusion of this set of trials was to use Transmit –Receive (Tx-Rx) and Absolute with both orthogonal and pan cake coils. Based on results on stress corrosion cracks in a stainless steel test plate the final design is a TR probe with 44 pancake coils 2mm diameter, separated by 3.3mm. The probe is operated with an RD Tech MS5800 instrument at 500KHz, using an X configuration. This has two rows of coils (offset by ½ coils) with a distance between them. Using it in TR mode, this pattern is the same one as the ‘X-probe’ commonly used for steam generator inspections. In this case, in reference to the arrows on the sketch in Figure 8, one coil is a transmitter while 3 others are receivers. Therefore, during each time slot, there are always 1 circumferential channel and 2 axial ones, as shown in Figure 9 below.

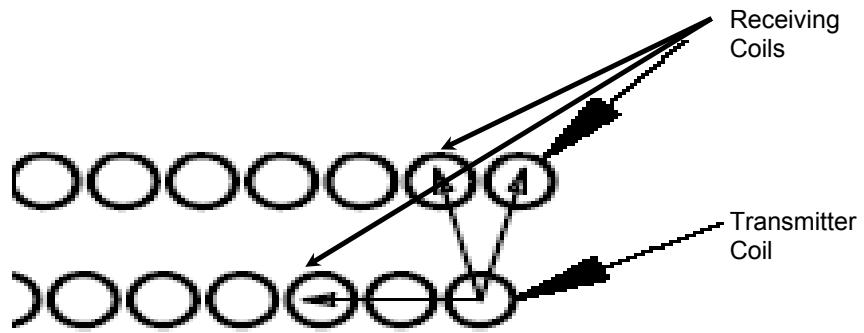


Figure 9 TR probe with 'X' firing configuration.

The equipment is shown in Figure 10 below. The probe is at the front connected to the MS5800, to the right is a stainless watertight box containing the multiplexer.

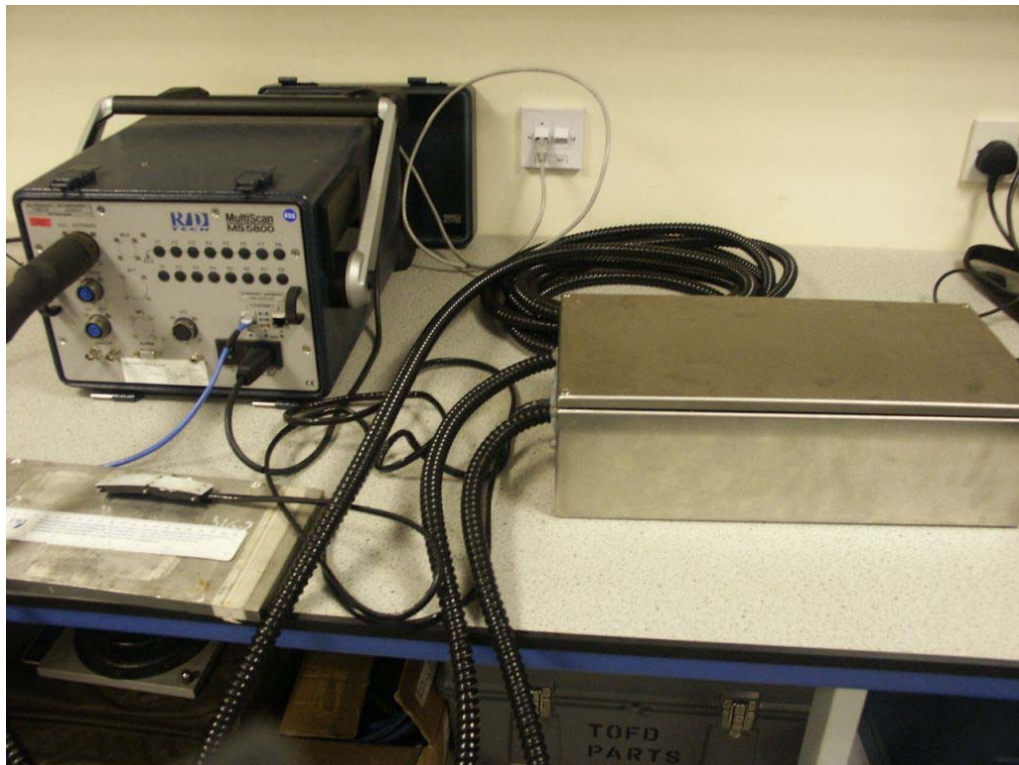


Figure 10 MS5800 Multiplexer and EC Array Probe

The c-scans (axial and transverse) obtained on the curved sample shown in Figure 7 are shown in Figure 11 below.

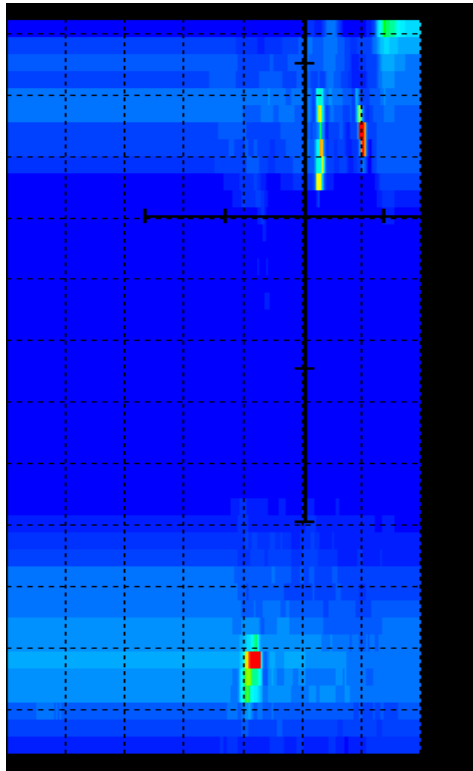


Figure 11a Transverse scan.

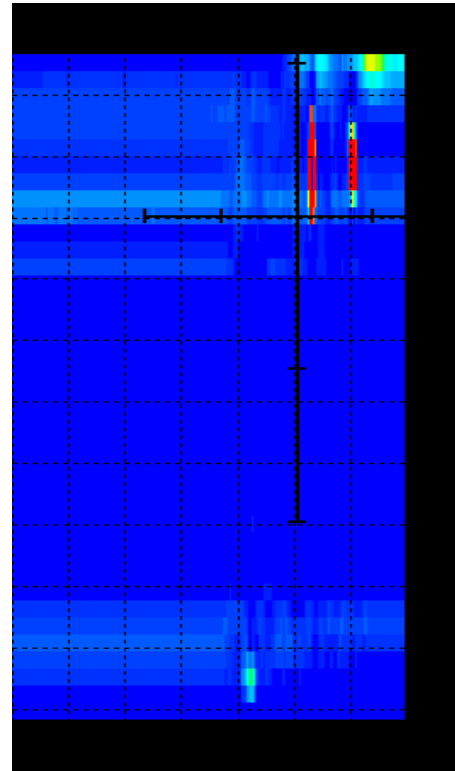


Figure 11b Axial scan.

1.3.5 The underwater wall climbing robot

The underwater robot developed by London South Bank University is designed to convey the scanning robot which carries and deploys the NDT sensors to the RPV nozzles. Three prototypes were designed and built, the final design is shown in Figure 12 below.

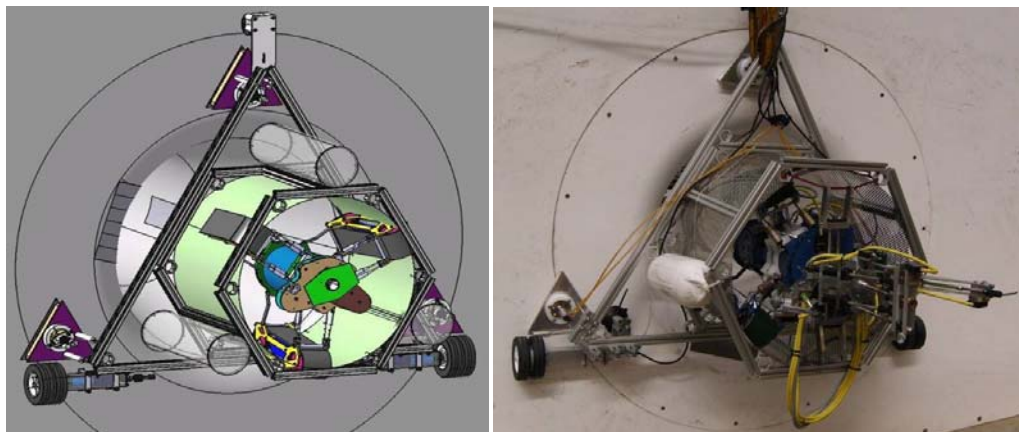


Figure 12 Final Prototype of Rimini wall climbing robot.

The robot uses a common principle to climb; which is to create a negative force to stick the robot to the wall. This is achieved using 3 sliding suction cups, with the suction created by centrifugal pumps driven by high speed air motors. The key advantage of this technique is

that expelling water creates a thrust force when the system is not touching the wall. The force pushes the robot towards the wall till the suction cup becomes attached to the wall.

The wall climbing robot was initially made neutrally buoyant so that very little traction at the wheels is required to climb the wall. However, the scanning robot that the climber piggy backs is not neutrally buoyant. Its mass in air is 55kg and in water it is 20kg. This represents a 20kg negative buoyancy force. The climber compensates for this by adding 20kg of positive buoyancy. The resulting combined system is then neutrally buoyant and the system climbs on the wall in exactly the same way.

However, when the scanner robot leaves the climber to enter a nozzle, the climber is left with a positive buoyancy force of 20 kg which lifts the robot to the surface. The solution to this problem was to add two underwater high friction suction cups that do not slide to the wall climbing robot. The cups are lowered to the surface by two pneumatic cylinders. Tests showed that the robot can hold itself in a parked state with up to 100 kg of positive buoyancy.

There are two ways to operate the suction cups to hold the robot in place. One way is to use compressed air to drive a vacuum valve and the second way is to use a water pump to create a vacuum. A water pump was used in the final version because of its small size and low power consumption that results in a simple low cost mechanism that (although not necessarily important) does not produce underwater bubbles and gives a silent system. The water pump used was an in-line LVM-117, Amazon pump of 24VDC with a capacity of 18litres/min.

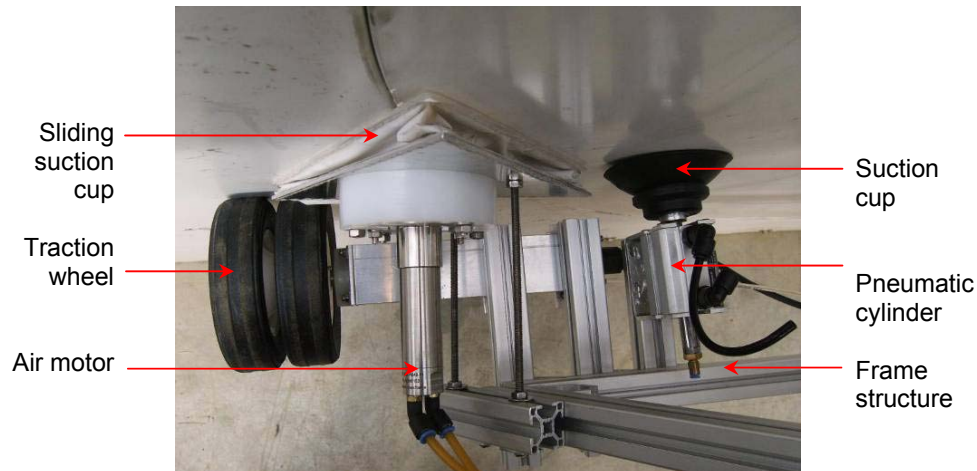


Figure 13 The suction cups and traction wheels on the LSBU underwater robot.

The robot is tele-operated in open loop with two 48V DC Maxon motors. Each single motor has its own driver and controller system. The two motors are sealed in water tight enclosures that are air pressurised via a compressed air supply cable to prevent water ingress into the motors in case of seal failures.

The robot is controlled in manual mode either from a PC notebook or wireless joystick control. All drive electronics and controllers are off the robot at the end of a 30m length of umbilical cable to reduce radiation exposure to the operators.

The traction wheels as shown in figure 13 are using a special sealing compartment development in the project to protect the motor of break down. It has a special mechanism to attach the motor onto the enclosure; however the motor shaft emerging from the air enclosure is sealed with a nitrile seal that is resistant to radiation environment.

The control system of the wall climbing robot is composed of a host computer, two out board PIC SC control modules, and one USB/RS485 board. The communication between the host PC and the control modules is over a short distance, but from the controllers to the motors the umbilical cable is 30 m long. Any number of the module combination can be used as long as the maximum allowance of 32 modules is not exceeded. The system can be easily expanded and the umbilical of the robot is just one very thin and soft cable. The schematic diagram of the system is shown in Figure 14 below.

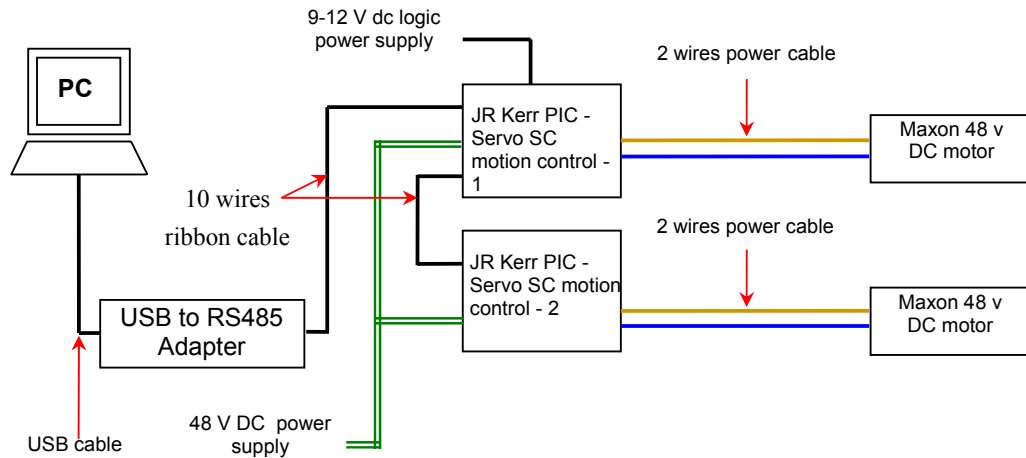


Figure 14 schematic diagram of control system.

1.3.6 The Zenon scanning robot

1.3.6.1 Design concept

The objective was to design develop and manufacture a fully functioning submarine robot, capable of carrying and deploying the NDT sensors and systems inside the RPV orifice. It is evident that the robot must be compatible with the LSBU carrier robot described above which travels to RPV nozzle and delivers the 'orifice crawler' onto the orifice opening. Consequently the system should be able to tackle and operate over all possible curvatures encountered during the travelling of the orifice crawler operation inside.

The robot will have caterpillar tracks and is an underwater pipe crawler robot that carries NDT sensors. The robotic system developed is capable of performing inspection on selected areas inside the orifice as shown in Figure 15 below with a variety of scanning routines. ZENON RTD provided sensor-based control and novel mechanism designs, to maintain the NDT sensor at desired surface contact forces or stand-off. Operator assisted navigation was developed and applied for the orifice crawler with the main objective of inspecting the under-investigation areas with the guidance of an operator and related sensory information. The robotic arm deployed by the tracked crawler is able to scan the austenite cladding to allow the detection of surface and near surface defects. Another capability is the deployment of NDT modalities to scan the lip of the nozzle in an orbital motion and also the capability to reach inside the nozzle to inspect the transition welds 700mm inside it.

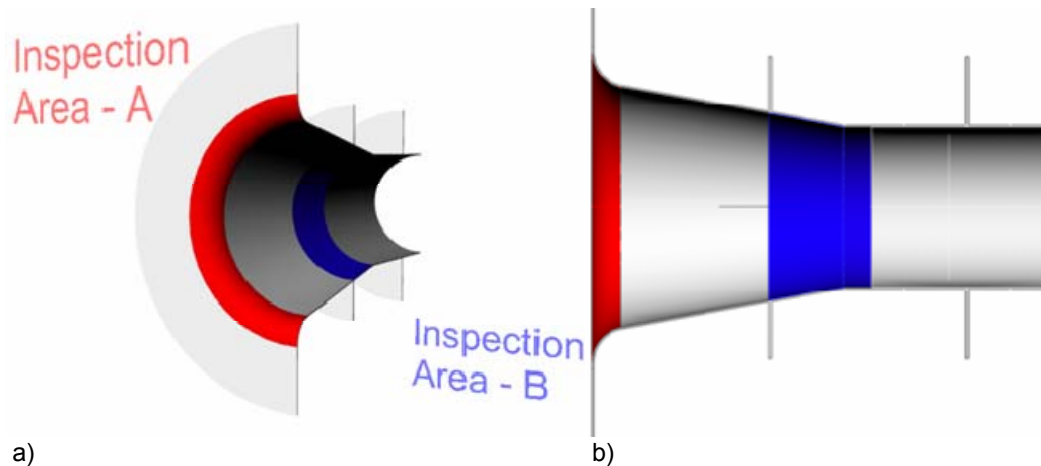


Figure 15 Scan areas of RPV nozzle:

- a) Out lip area A;
- b) Safe end weld area B.

The final design of the crawler is shown in Figure 16 below a) is the front and b) the side view

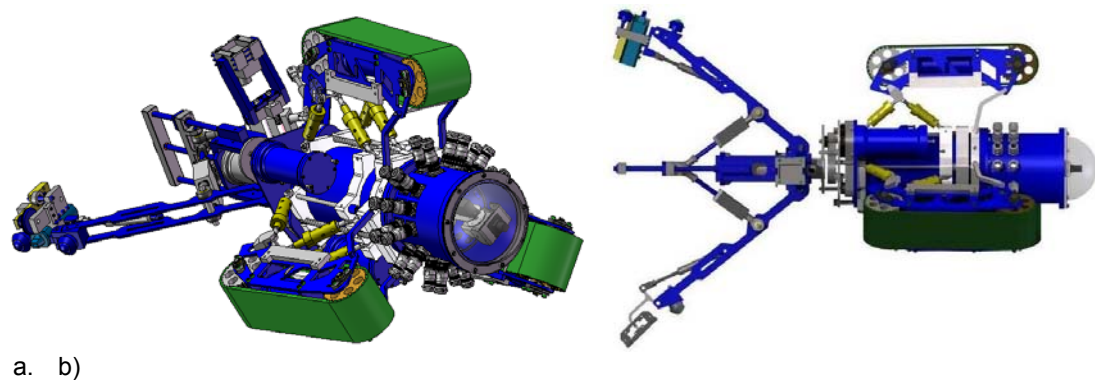


Figure 16 Scanning robot:

- a) Front view;
- b) Side view, the NDT scanning arms are at the rear - on the left.

1.3.6.2 Software

A principal component in the RIMINI crawler project is the software controller that will guide the mechanical system and will enable it to perform the various tasks for which it was developed. The software provides functionality for tele-operating the robot using position and speed control of all nodes, as well as displaying readings from the various sensory modules and health information such as current draw. Two-way communications implemented using standard RS232 connection using the serial data protocol provided by Maxon. Control is achieved using a client GUI application running on the operator's laptop.

The robot software executes on two interacting computer systems: the robot controllers; and the off-robot PC. The controllers communicate with the off-robot PC via a serial interface (RS232->RS485->RS232->CANOpen). The Rimini control Software was written entirely in the C++ programming language, using a number of in-house, purpose-built, and third-party API libraries. The various components that comprise the software and their inter-dependencies are illustrated in Figure 17 below.

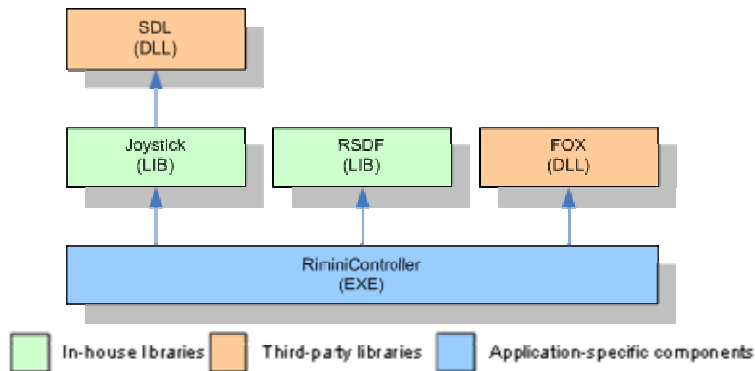


Figure 17 Library dependencies for the Rimini software.

The Joystick and RSDF (Robotics Software Development Framework) libraries are in-house, general-purpose API libraries. The FOX dynamic library offers an API for designing Graphical User Interfaces (GUI). Finally, the Rimini application offers an implementation of a GUI through which a user can configure and control the Rimini robotic crawler. The Rimini Controller application offers an easy to use yet powerful GUI that facilitates the operation of the crawler and NDT deployment. Operation is manual, in which case the user clicks on the controls and the robot responds immediately.

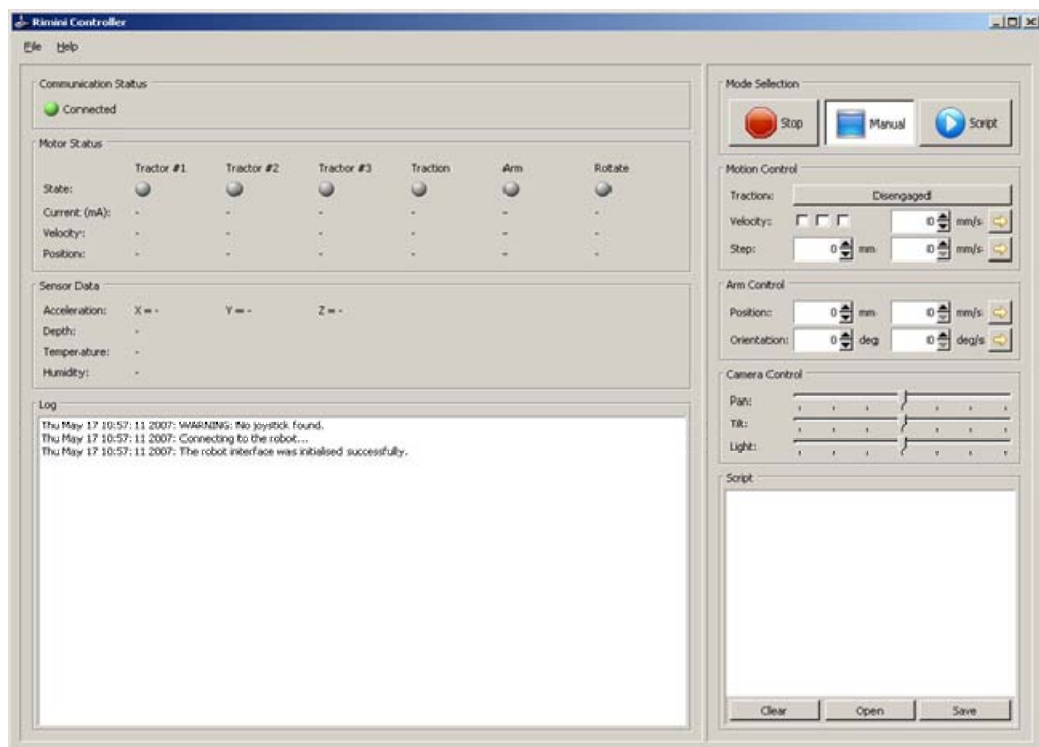


Figure 18 RIMINI graphical user interface (GUI)

Figure 18 depicts the GUI of the application. The left part of the screen consists of indicators that show the current state of the crawler. These indicators include the state of the connection to the robot, information about the status of the various hardware and electronics components, the state of the track units, sensory information (tilt, depth meter, temperature, humidity inside enclosures). The right part of the screen holds the controls that allow the user to operate the robot. The operator is given the capability to engage/disengage individually each tractor in order to be able to centralise the crawler while entering the orifice. Other control capabilities include on-screen controls of the pan-tilt camera and lightning intensity unit. All these features are implemented also on Joystick. The software was installed on a lap-top computer and integrated into one control box with pertinent power electronics, vision interfaces and encoder outputs for the NDT instrumentation. The related NDT instrumentation including the instrumentation of EC probe, the variable frequency oscillators for the ACFM probe and the balanced-bridge sensing circuits for the ACFM coils and the Phased Array Electronics where used in conjunction with the crawler control box while necessary TTL START-STOP signals were sent to the NDT instrumentation from the crawler control box when necessary.

The components of the overall man-machine interface are shown in Figure 19 below.

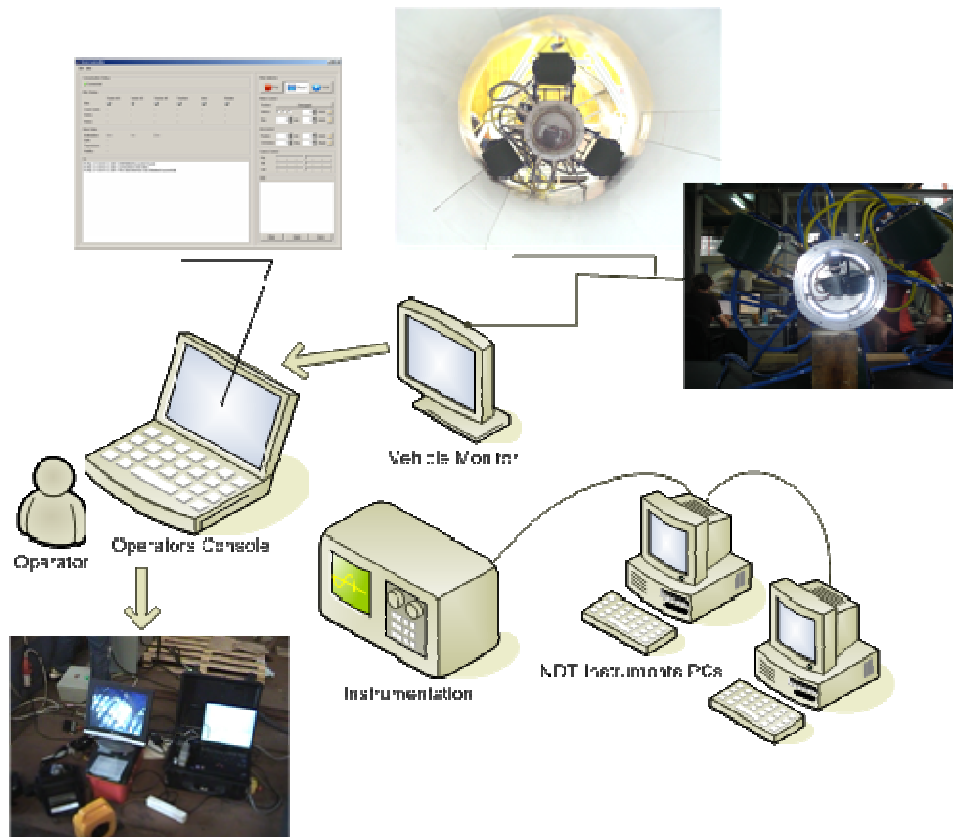


Figure 19 Man machine interface.

1.3.6.3 Final NDT arm design

Overall the Inspection-Arm MK2 design consists of the sensor holder/positioning subassemblies (EC and ACFM holders, P/A Holders, encoders) and a mechanism that controls the angle / opening of the two arms. The two arms seen in that system are able to rotate around their edge. The rotational DOF in each arm is driven by a lead screw mechanism actuated by a marinised motor. The principle is similar to the one of an

umbrella. By rotating the lead screw a stage is moved back and forth and an articulated mechanism is actuated.

The rotary movement of the arm is performed from the SA2 module and the output shaft. In order to control the scanning diameter of the arm an additional motor was integrated within the arm that incorporates the same design philosophy with the other underwater motor enclosures that constitute the motion production elements of the RIMINI crawler. Here the overall design of the SA5 module is outlined. The design of this module was quite demanding and passed from a significant number of design cycles and changes. Continuous communication guaranteed that the finalised solution was inline the inspection needs of the NDT partners. To this end the system was capable to inspect all areas of the orifice and the system was tuned to inspect in fine detail the inspection areas A and B as seen in Figure 15 above.

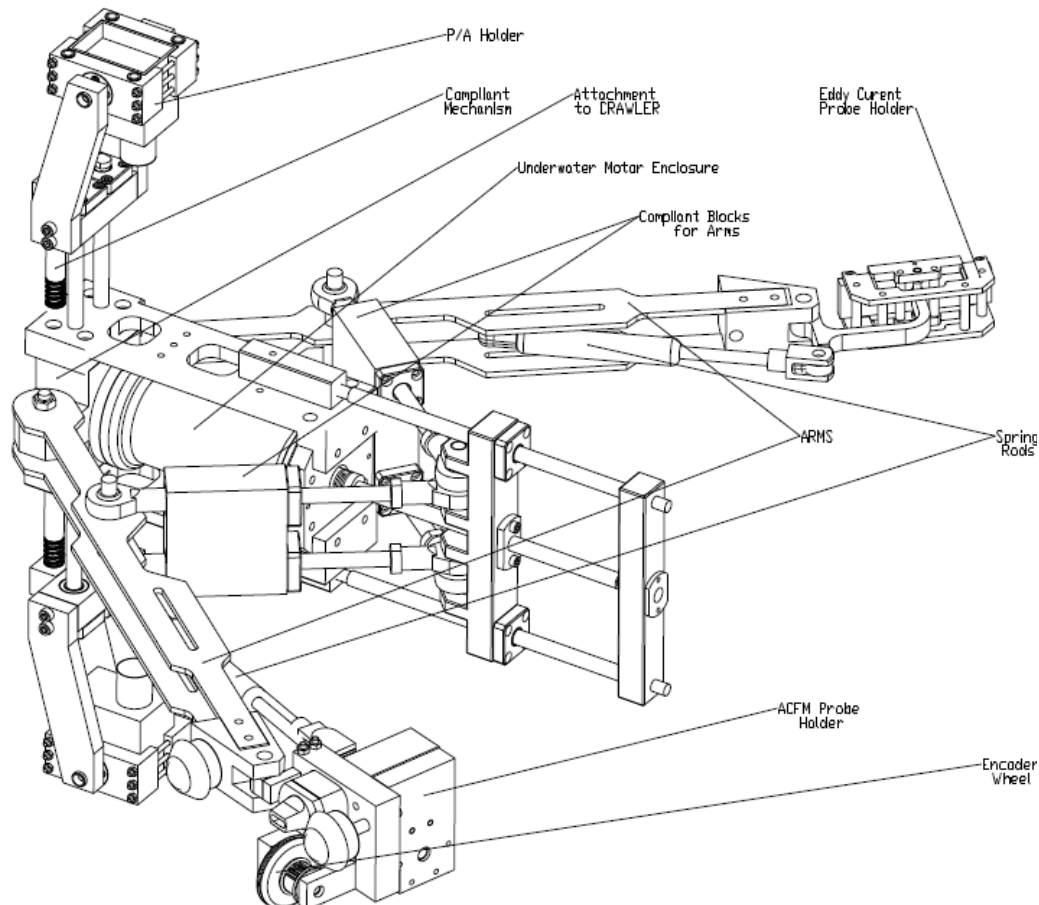


Figure 20 Design sketch of the inspection arm

The initial deployment of the scanning arm on the outer round weld (first inspection area) is performed via the use of a lead screw being actuated by an additional DC motor, positioned in a custom-made underwater enclosure which ensures untroubled operation and continuous feedback by the use of a rear mounted rotary encoder. The specific solution intends to provide the scanning procedure with the appropriate flexibility regarding the control of the rear arms extension and passive compliance. Each arm is connected to the lead screw by the use of a custom made connector and interfacing compression mechanism. Each mechanism is comprised by a machined block and two separate compression springs which form a type of suspension. It has to be noted at this stage that

during the continuous motion of the system inside the nozzle, several sensors ensure the accurate compensation of the gradual system's scanning diameter adjustment as well as overall procedure monitoring. By applying such a design the arms are positioned with accuracy in relation to the under-inspection nozzle. The scanning arm has integrated compliant mechanisms in order to compensate for the potential loss of NDT probe contact and cope with the crawler eccentricity in relation to the nozzle. Additionally the positioning of the sensor and the encoder mechanism is achieved by the use of this secondary passive compliance mechanism. The articulated mechanism re-presented in Figure 19 is inserted into a compliance block. Each block contains two springs that provide the needed compliance to the inspection-arm up an additional stroke of 80mm (in the sensor tip). Main reasons for selecting a compliance mechanism are:

- 1 The need to avoid impact with the inner surface of the nozzle that the arm cannot withstand.
- 2 The need to adjust the desired force applied to the positioning ball units to a normal working condition of 60N.
- 3 The need to compensate any misalignment caused by crawler eccentricity in respect to the under-inspection nozzle.

1.4 Project achievements against state-of-the-art

The following table summarises the technical achievements of this project and compares them against current state of the art alternatives.

Current state-of-the-art	Rimini system
Linear phased array probes	Advanced 2D TRL phased array for stainless steel
32/128 phased array instruments	Full parallel 128 2D phased array instrument with matrix data capture
Complex hard to use ultrasonic models	Simple fast validated ultrasonic models.
Ferritic ACFM	Calibrated stainless steel ACFM
Multi channel eddy current probes	Flexible multi channel eddy current probed for nuclear applications

1.5 Impact on the nuclear industry

The implementation of the NDT technologies embodied in the Rimini system will provide higher reliability and repeatability for the inspection of RPV's. Initially this will only be of 'Safe End' welds, however by modifying the design of the robot it will be possible to use the technologies on many other applications.

2 Dissemination and Use

2.1 Rimini inspection system

Interested parties should contact:

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