

Wall Climbing And Pipe Crawler Robots For Nozzle Weld Inspection Inside Nuclear Pressure Vessels

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Abstract: This paper describes the design and development of a NDT robotic solution to test circumferential welds located inside pipe nozzles at a distance of 700mm from the inside walls of nuclear pressure vessels. These welds are currently inspected using very large robot arms that are taken into the containment area and assembled. This is a time consuming operation that exposes operators to radiation. A preferred solution is to develop a light weight and compact robot that can be carried into the containment area and inserted into a pressure vessel using an overhead crane. The crane is then removed and used for other tasks. The robot must then be operated to accomplish the weld inspection task in all the pipe nozzles located in the pressure vessel.

Keywords: NDT of Pressure Vessels, Nozzle Weld Inspection, Underwater Wall Climbing Robots.

I. INTRODUCTION

There are 450 nuclear power plants around the world and 210 are in Europe. They provide approximately one-third of total electricity produced in the EU [1]. This number is forecast to increase by 8% to 2010 and then double and treble by 2020 and 2030 respectively [2]. Nuclear power is the most environmentally friendly form of generating electricity with respect to the production of green house gases. The world stock of nuclear plants is ageing and eight currently operating nuclear units are over 40 years old. This figure is also forecast to rise as more utilities seek to extend the life of ageing plant. Keeping Europe's long-serving nuclear reactors in good shape is a prime concern for industry and policy-makers. [3]. The risk of defects due to corrosion and other effects rises with age of nuclear plant. Nuclear disasters due to structural failure are rare but the social, environmental and economic consequences can be enormous. Risk of failure can never be eliminated entirely, but the progressive reduction of risk and consequent increase in safety is a major driving force in the nuclear industry worldwide.

The safe operation of the nuclear power plants depends on the regular in-service inspection of the reactor pressure vessels, which contain the nuclear fuel. Reactor Pressure Vessels (RPVs) which house the fuel of a nuclear power plant are made of thick steel sections welded together. The RPV is made up from thick ring, dome and nozzle sections welded together. This steel becomes brittle with age (and length of exposure to radiation) and is therefore more susceptible to the rapid growth of [4]. These RPVs contain water under high pressure and are particularly susceptible to a process known as 'stress-corrosion cracking' [5]. Regular, rigorous inspections

are thus demanded by the regulatory authorities to demonstrate the continued structural integrity of the RPV, searching for unexpected degradation mechanisms such as thermal fatigue and stress-corrosion cracking. Failure of an RPV would be a totally unacceptable event, with enormous social, environmental and economic consequences.

The first indication of cracking of a PWR/RPV (Pressurised Water Reactor/RPV) 'head penetration' was discovered at Bugey 3 in France in 1991. This was originally thought to be an isolated phenomenon until cracks were also discovered at Ringhals 2, Sweden in 1992. From that moment the problem of stress corrosion cracking was considered to be generic in this type of reactor [6]. As recently as 2001 the RPV at Davis-Besse [7] nuclear power plant in the USA was found to have corrosion penetrating 150mm into the steel plate over an area of 100x125mm. It is believed that this had developed over 2-3 years without being detected. The investigation, which followed, concluded that visual inspection in this area was no longer adequate and should be supplemented by ultrasonic or eddy current testing. The US Nuclear Regulator ordered operators of 68 other reactors, similar to Davis-Besse to look for similar problems. In 2002 through-wall cracks were found in the RPV welds at North Anna 2 in the US causing the plant operator to replace the RPV head immediately. US nuclear operators plan to replace a total of 29 RPV heads by 2007. The Russian build variant of the PWR, known as the VVER, is also susceptible to cracking in the RPV. This design of reactor is currently operating in: Armenia: 1 unit, Bulgaria: 6 units, Czech Republic: 6 units, Hungary: 4 units, Russia: 15 units and Slovakia: 6 units. Thus making inspection of RPVs crucial to Europe.

II. THE INSPECTION ENVIRONMENT

The inspection of RPVs inside nuclear plants is carried out during periods of maintenance activity. This is called an "outage" and happens on average every 1-5 years [8]. During this period, the reactor is shut down and is thus not producing any electricity. The cost to the operator for a planned outage is 0.8 million Euros per day, while the cost of an unplanned outage is up to 1.6 million Euros per day [9]. The inspection tasks are carried out at the same time as other maintenance tasks. The whole operation is planned months in advance to reduce the days of the "outage" to a minimum as the cost of each additional day of inspection is 0.8 million Euros. It is essential that the inspection operation must not interfere with other maintenance tasks during an "outage."

Present methods of inspection of RPVs include two inspection technologies. These are ultrasonic and eddy current

technologies. Currently both have several limitations. In order to determine whether the weld has defects or not, the operators have to conduct an ultrasonic and eddy current inspection. After emitting ultrasonic wave to the suspected welds, they monitor its reflected signal. Usually reactor pressure vessel is manufactured by welding several parts together. The welds to be inspected in the vessel are largely classified as circumferential welds and nozzle welds.

Circumferential welds include the welds of flange to upper shell, upper shell to middle shell, middle shell to lower shell and lower shell to bottom head, while nozzle welds include the welds of nozzle to middle shell, and nozzle to nozzle pipe so called safe end. Flange ligaments are also inspected. In some reactor vessel, vertical welds of reactor shell and safety injection nozzle welds are included in inspection item.

When inspecting each weld, the operators have to use various incident angles of ultrasonic wave for more accurate and strict inspection.

For example, in case of reactor shell welds inspection, they use incident angles of 0, 45, 60, 50/70 degrees, respectively. In addition, for each incident angle, they have to scan the welds in four directions: upward, downward, clockwise and counter clockwise direction by using an ultrasonic probe with specified incident angle. Thus they have to inspect the welds seventy seven times in total.

Most RPVs have at least six nozzles, thus the number of nozzle inspection becomes sixty times, and the number of circumferential weld inspections becomes sixteen times. This means that tens of different types of probes and scan patterns are used during a RPV inspection thus requiring many days to inspect one RPV.

Current RPV inspection methods involve operators working for long periods of time in reactor containment areas whilst exposed to radiation. Figure 1 shows the removal of vessel cap, followed by the assembly of a large robot and its insertion into the vessel before non-destructive testing (NDT) can be carried out.

III. ACCESS TO WELDS WITH A CLIMBING ROBOT

An underwater system is required for the inspection of RPVs in nuclear reactors as the RPV is filled with water to reduce radiation levels. Thus all inspection systems have to operate under water.

This European funded project, called RIMINI-Inspect [10], is developing a small prototype tele-operated robotic inspection system for detecting defects and corrosion in the circumferential transition welds into the nozzle in reactor pressure vessels. Figure 2 shows the concept. The priority on this project is to obtain a new generations of NDT sensors, actuators and systems for health, safety and security of people and environment.

The robot is required to inspect a circumferential weld located 700mm inside the nozzle pipe. RIMINI-Inspect has developed a compact wall climbing robot that can be carried into the containment area by at most two people and lowered into the vessel. It then operates underwater, moving from one nozzle to another to provide access to nozzle openings. A

scanning arm is then required to perform NDT inside the nozzle. Figure 3 shows a conceptual drawing of such an arm.

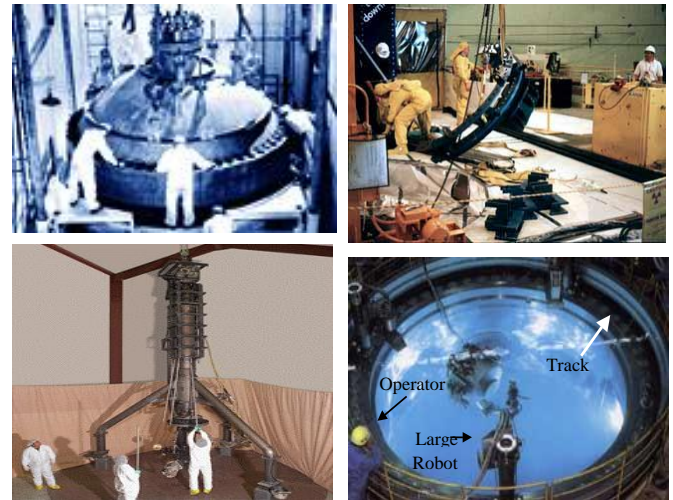


Fig. 1: Operators getting ready for inspection of RPV, assembling large robotic inspection manipulator in the reactor containment. Exposes operators to radiation.

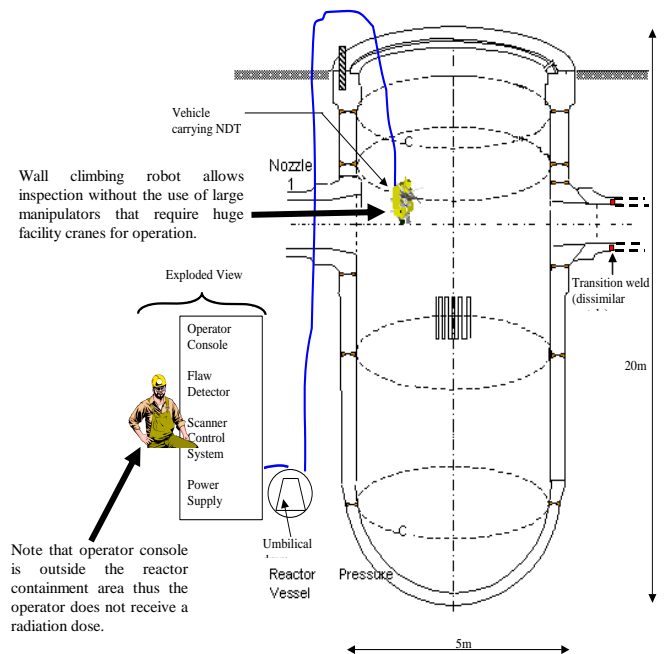


Fig. 2: Conceptual design of RIMINI system based on a small submarine robot carrying advanced phased array ultrasonic and eddy current inspection sensors and techniques.

The fully extended robotic arm would centralize itself when inserted into the nozzle with the aid of locating arms as shown in figure 4. The scanning arm would start just above the surface and travel 700 mm into the nozzle to reach internal weld. The internal diameter of the smaller pipe where the weld is located is 540 mm.

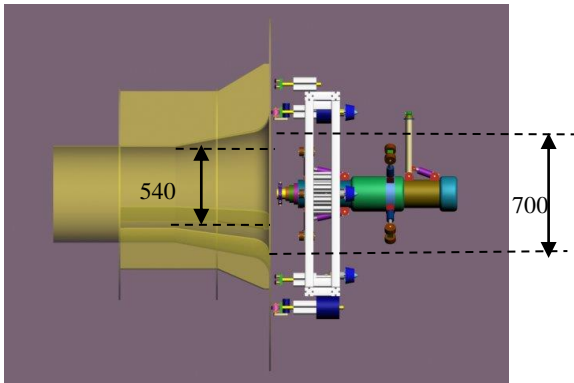


Fig. 3: Main arm shown in fully retracted position on the inside wall of a RPV (Conceptual Design).

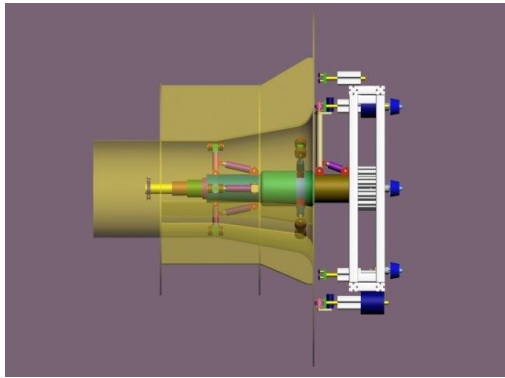


Fig. 4: Fully extended robotic arm inserted into nozzle (Conceptual Design).

This arm was evaluated but eventually rejected as a solution to the problem of getting access to the weld located inside the nozzle. The solution adopted was to develop a second mobile robot that would inspect inside the nozzle.

IV. NDT REQUIREMENTS AND TECHNIQUES

Major development in the inspection methods and sensors for the inspection of RPVs even under thick cladding. The RTD partners are helping 6 SMEs develop 2 new NDT techniques, which will result in rapid in-service inspection methods for the inspection of safety critical welds in RPVs. These are based on the development of:

- Phased Array Technology (this reduces the need for multiple scans of one weld area by electronically moving the ultrasonic beam). Main innovation is in developing novel ultrasonic multi-element phased array sensor and systems with 3D focusing capability (not yet available in any current systems) for the detection of defects in RPV welds e.g. fatigue cracks, inclusions and other flaws. Peak NDT and TWI have shown some possibilities with 2D focused probes to increase the ultrasonic intensity at a defect thus demonstrating the possibility of their equipment in detecting smaller defects resulting in a higher probability of defect detection for safety

critical defects. Furthermore the technology developed will be able to accurately size defects because positional errors can be minimized using phased array technology.

- Eddy Current Array Technology will be developed, which has the advantage of wide area coverage. Main innovation is increasing the capability of the technique to detect not only corrosion but also other defects. Currently the technique can only detect corrosion through 5mm of coating thickness. This will be increased to 10mm. Also the project will lead to drastic improvements in probability of defect detection in the near surface region by the development of the new and novel eddy current arrays.

V. DESIGN OF ROBOTIC SYSTEM

After preliminary investigations and development of systems that were considered likely to be required for the submersible wall climbing robot, the final design dispensed with the idea of a telescopic arm, preferring instead to carry a mobile robot on the wall climber. The second robot would enter a nozzle pipe to provide access to the circumferential weld located 700 mm inside the nozzle. A working prototype of the robot vehicle has been built to half scale and tested in a laboratory tank. The robot is to half scale because the laboratory tank is not large enough for the full version.

The prototype is shown in figure 6 on the left hand side. The drawing on the right hand side shows the piggy-back robot which is carried in a tube. This robot will enter a nozzle pipe after the climbing robot has been positioned over the nozzle opening, and travel into the pipe to inspect circumferential welds located at a distance of 700mm from the lip of the nozzle.

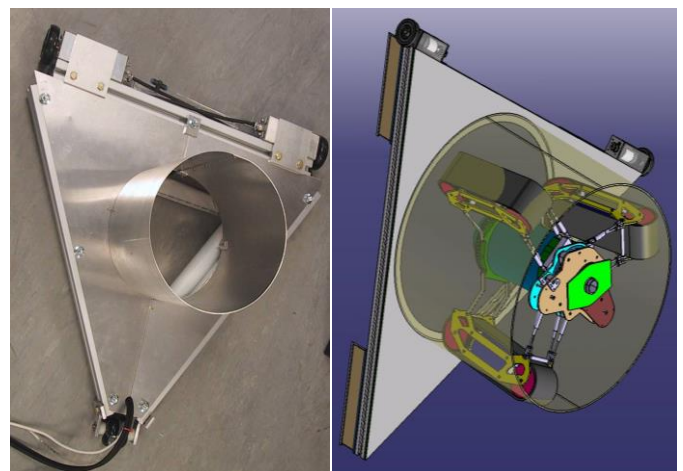


Fig. 6: Prototype Wall Climbing Robot on the left. On the right is a technical drawing of pipe crawler inside its carriage tube.

The wall climbing robot adheres to the wall of the pressure vessel by using three vacuum suction cups placed at the vertices of the triangular chassis. These cups are dragged

along on the surface by the wheeled motion of the robot. The design of the suction cups is critical with regard to materials that provide a low coefficient of friction and are water tight as well as flexible. A large effort has been expended in finding suitable materials and constructing the optimal suction cups.

Motion of the robot is actuated by two independently controlled DC servo motors sealed in two air purged enclosures. All electronics such as the control systems are placed off-board the robot because high radiation will destroy the electronics circuits if placed on-board.

A. Materials Allowed In Reactor Pressure Vessel

Considering radiation hardening, special materials have to be used in the reactor vessel, mechanical and electrical equipment have to survive total doses of 300 Krad (Si) to 1 Mrad (Si), (See Table 1)

Thermoplastic materials that can tolerate gamma radiation without problems include low-density polyethylene, linear low-density polyethylene, high-density polyethylene (those containing phosphite stabilizers may yellow), polyethylene terephthalate, polystyrene, polycarbonate, and nylon.

Thermoset and rubber materials that can survive gamma radiation without problems include phenol formaldehyde, urea formaldehyde, natural rubber, nitrile rubber, aluminum anticorrosion and stainless steel.

Special radiation resistant grades of PP are needed for resistance to gamma radiation, because PP does not stand up well to radiation. Normal PP grades yellow noticeably, become brittle, and crack over long-term exposure. Special radiation resistant PP grades, with special stabilizers, are available. Also, PP copolymers are more resistant than PP homopolymers.

Problems develop with the irradiation of polyvinyl chloride (PVC) or fluoropolymers such as Teflon and are therefore avoided.

B. Robot Chassis

Constructed with Bosch Aluminum profile and brackets, the main idea is to minimize the weight of the wall climbing robot, reduce the robot profile to be as near as possible to the surface and obtain neutral buoyancy in the water. These physical conditions guarantee reduce the momentum over the suction cups, where these forces are already existent in the carriage tube for the weight of the scanning robot arm and in the full umbilical cables, however the structure permitted modify completely all the geometry of the robot and add any other equipments, cameras, thrusters, sensors etc.

C. Motion Control

The design uses 2 standard DC motors for motion control of the climbing robot. These are housed in a sealed and air pressurized aluminum enclosure with supply of compressed air to half bar from a reservoir. This is to prevent ingress of water and to prevent possible contact of irradiated water with copper windings. Using air also prevents the possibility of contamination by insulating oils.

There are no shaft encoders or position/velocity sensors mounted on the motors.

PWM Servo drives and amplifiers for the motors are placed out of the cell. Cable lengths from servo drives to motor are around 30 m.

Conventional motor and motor controller in radiation-intensive environments are susceptible to high-energy gamma radiation particles that will attack the motor materials. Usually, the organic compounds are most susceptible to breakdown by radiation, and as a result the lubricants, varnish, lamination bonding, and cable insulation in standard, commercially-available motors will all deteriorate over relatively short periods of time.

Hence it is essential to use suitable radiation hardened DC motors, cable and connectors.

Products commercially offering are available with Radiation hardened that will enable one-to-one replacement of the standard motors on the demonstration prototype.

Since failure modes of the robot will not lead to environmental disasters when subjected to massive doses of radiation, it may be sufficient to use Motors with 2×10^8 Rads TAD and replace components when damaged. Although the replacement of components is expensive, there may not be a need to lengthen useful life of the motors. Particular Companies^[11] claims that its motors can survive a dose as high as 10^9 R. without changes in performance. They also supply radiation hardened Gearheads, Brakes and Cables.

For positional and velocity control, two odometers, thin wheels with brushless resolvers driven directly by the shaft of the wheel assembly, will provide feedback to the out of cell controller. In this way, the position and velocity of the robot will be tracked. This feature will eliminate the mechanical errors of the motor and gearbox from the feedback loop.

The motor shaft emerging from the air enclosure is already sealed with a Nitrile seal that is resistant to radiation.

Motion of the wall climbing robot is controlled by tele-operation with a digital joystick.

Straight-line forward and reverse motion, and rotate right or left movement is pre-programmed at three speeds.

Radiation hardened resolvers, both motor mounted and stand alone, as well as RDE resolver-to-digital converters are commercially available.

Hence, radiation hardened DC motors, cables, gearboxes and resolver assemblies can be selected on a more or less one-to-one basis to replace the components of the demonstration prototype.

D. Adhesion of Robot to Vessel Wall

The robot uses three specially designed suction cups to adhere to the wall. These are constructed from canvas and nylon which should resist irradiation damage. The cups have sufficient flexibility to adapt to surface curvatures on the pressure vessel when the robot rotates on the wall.

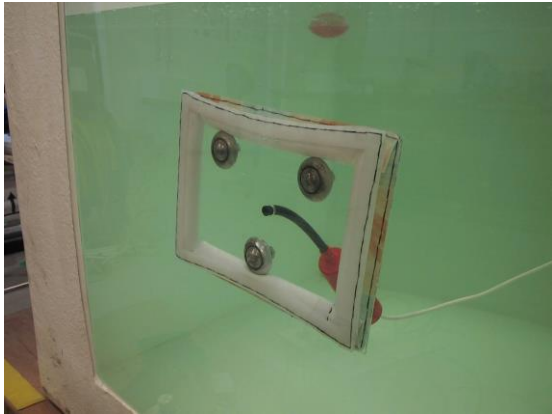


Fig. 7: Suction cup with electrical submersible pump adhering in a water tank to a glass wall

Electric centrifugal submersible pumps of polyacetal plastic with 18 litres/minute to 1 bar are currently used to create suction in the trial prototype (see figure 7). By Bernoulli's principle for incompressible fluids flow can be analyze the suction cup creates a pressure directly proportional to the differences of the areas between pump and suction cup (see figure 8). These pumps will be replaced by three industrial deep well Electric submersible pumps of stainless steal to provide suction forces and thrust forces to push the robot to the wall after lowering it into the pressure vessel.

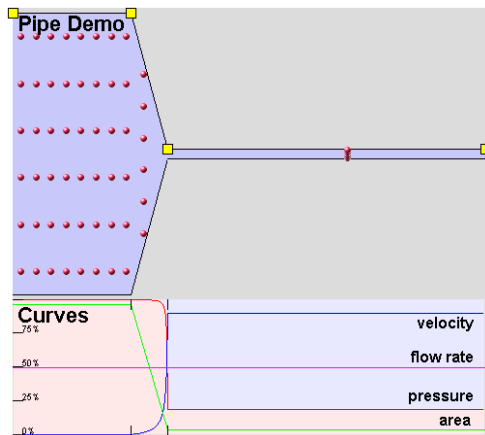


Fig. 8: Physic of fluid flow Bernoulli's Principle Source: M. Mitchell

Controlling the voltage of the electric pumps offers additional flexibility to control the amount of adhesion force during motion of the robot and while it is parked over a nozzle with fully force to deploy the inspection robot.

VI. INSPECTION ROBOT (ZENON)

The robotic nozzle inspection unit will be submerged at a depth of approximately 10m to 15m in order to inspect the reactor's nozzles. Therefore the design must take into account the fact that all working elements need to be

waterproofed.

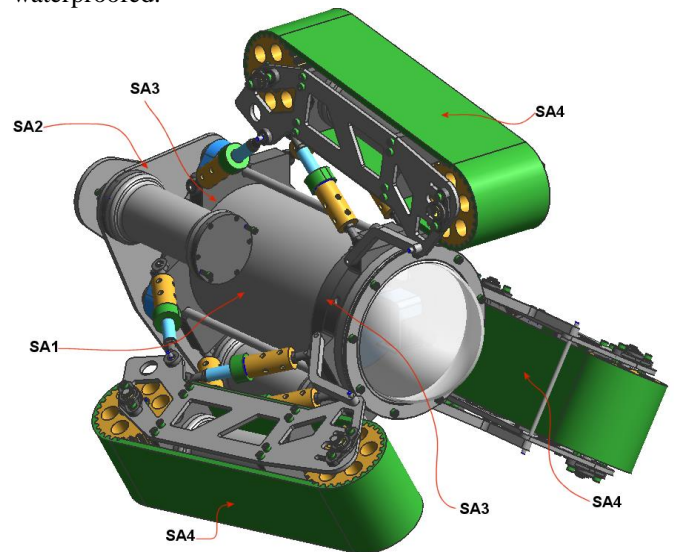


Fig. 9: Nozzle inspection vehicle and subassy

The Fig. 9 above displays the main body of the robot and the respective subassemblies (SA). SA1 is the electronic compartment unit that serves also as the main body of the robotic unit. It contains all the necessary interfaces of the electronic elements that actuate the ROV plus the pan/tilt camera for visual inspection inside the RPV nozzle. SA2 in the rear is an interfacing structure that holds two underwater motors that actuate the underwater tracks (SA4) and provides the necessary rotary actuation to the nozzle inspection arm. SA3 is the actuation module that forces simultaneously the tracks towards the nozzle. Due to the fact that the RPV nozzle is an axis symmetric shape that has continuously variable diameter the tractor support (SA3) provides suspension capabilities in order to cope with the nozzle diameter change.

The main body and most of the components were made by aluminium 5083, which is used particularly in water. It should be stressed that the vehicle is designed for proof-of-concept purposes and radiation proof materials were also realised whether the proposed system will be exploited for real servicing in radiated environments.

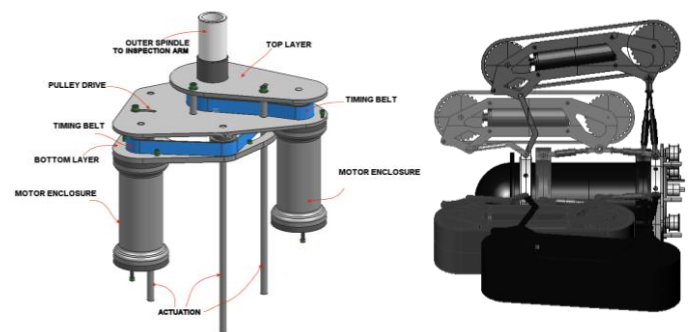


Fig. 10: Actuation mechanism of the inspection robot (Left) and (Right) two operational modes, system stowed & system fully deployed

The tracks will be deployed using a mechanism situated around the electronics compartment (SA2). This will have the function of a triple linear actuator. The three screw drives equidistant from the crawler's centre, will push a ring along the body of the electronics compartment, which in turn is going to lift three sets of levers, forcing the tracks to deploy. As mentioned this feature provides variable deployment to suit different working diameters, as well as the ability of negotiating better with tube bends. All three screw drives will be powered from a single motor. Power will be delivered to each screw drive by using a chain arrangement. The current design can be carried inside a hollow cylinder 430mm in diameter (ID) and can traverse inside a tube of up to 600mm in diameter. The modular design realised can decrease the lower and increase the higher operation diameter limits respectively.

Each track system encompasses its associated motor. In the current design the tracks are 400mm in length, 100mm in width and height. Fig. 10, illustrate the operation of the deployment mechanism.

The NDT arm holder is a subassembly of the nozzle inspection robot. It serves the purpose of locating the NDT sensors on the surface that must be tested.

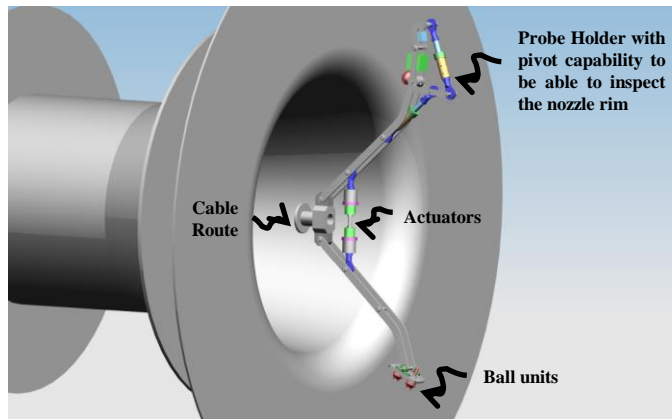


Fig. 11: Main characteristics of the inspection robot Arm

The holder is able to rotate around the nozzle's axis. This degree of freedom provides the ability of a +/-180 degree rotation around the nozzle's axis, which, combined with the movement of the inspection robot, covers the entire internal surface of the nozzle inspection area. The rotational movement is controlled by a motor while the accuracy and position of the rotation is monitored by an encoder. The later is attached next to probe sensor.

In order to be able to scan within a range of radius the mechanism has been equipped with two extension springs (actuators) which provide the sensor with the adequate contact force and the ability to follow the internal surface of the nozzle. The maximum applied force is 180 N while the working force is expected to be at about 160 N

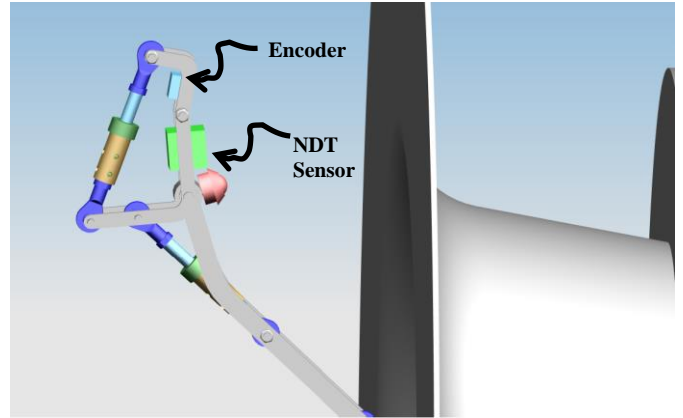


Fig. 12: Sensor holder of the inspection robot Arm

The two arms are equipped with ball units in order to move across the nozzle without heavy opposing forces due to friction. The ball units also ensure that neither the sensor nor the encoder need to endure the forces created by the basic spring set (figure 10). We chose ball units because they provide movement in any direction and at a variety of positioning angles. Moreover they ensure stable movement of the mechanism which we considered to be vital for the scanning process.

The secondary arm has a set of two ball units. The ball units are carried by a small platform.

VII. TABLES

TABLE I: RADIATION RESISTANCE OF COMPONENTS

Technology Comparison	Radiation Tolerant	Radiation Hardened	Strategic Radiation Hardened
Total Dose	<300 Krad(Si)	300 Krad(Si) to 1 Mrad (Si)	>1 Mrad(Si)
Dose Rate Upset	<10 ⁷ rads(Si)/s	10 ⁷ - 10 ¹⁰ rads(Si)/s	>10 ¹⁰ rads(Si)/s
Dose Rate Survivability	<10 ¹⁰ rads(Si)/s	10 ¹⁰ - 10 ¹² rads(Si)/s	>10 ¹² rads(Si)/s
Single Event Upset	>10 ⁻¹⁰ errors/bit-day*	10 ⁻¹⁰ - 10 ⁻¹¹ errors/bit-day*	<10 ⁻¹¹ errors/bit-day*
Single Event Latchup	Immune	Immune	Immune
Neutron	<10 ¹² MeV-cm ² /mg	10 ¹² -10 ¹⁴ MeV-cm ² /mg	>10 ¹⁴ MeV-cm ² /mg

Source: Honeywell systems

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