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Abstract
The Centre was established in 1992 to research and develop inspection robots and NDT techniques to [1,2]:

- Bring automation to the NDT task to eliminate errors caused by human operators due to fatigue on jobs that require a great deal of inspection in difficult environmental conditions.
- Improve defect detection by using the ability of robotics to improve sensor probe positioning accuracy and repeatability and use the programmable flexibility of robots to optimally deploy a wide variety of sensor probes and inspection techniques.
- Reduce the cost of performing the inspection by using wall climbing and mobile robots that provide access to test sites that are remotely located on large structures and/or in hazardous environments and hence not easily accessible to humans.
- Reduce costs substantially by performing in-service NDT with robotic deployment of sensor probes thereby eliminating outage costs and production losses.
- Reducing capital equipment costs by developing compact multi-function inspection robots that can flexibly perform a variety of different NDT tasks on different sites. Thus the robots should be readily transportable between different sites, be able to move over floors, change surfaces and climb walls, ceilings and other structures of variable curvature whilst carrying a payload of NDT sensors that can scan test surfaces by deployment with multi-axis arms.

Introduction
We believe that the long term future of Non-Destructive Evaluation (NDE) rests in the minimisation of the role of the human operative in the manufacturing and process sectors as well as in-service Non-Destructive Testing. We envisage a future in which it will not be necessary to send large numbers of operatives, in scarce supply, to NDE sites. Instead measurement processes will be made remotely making extensive use of continuous monitoring, non-contact sensors and by the deployment of robotic devices to gain access to the test site when it is in remote, or hazardous locations. The remaining role of the Human NDE practitioner in such a scenario is at once safer and more intellectually exciting.

Application areas for automated and robotic NDT are in the inspection of critical infrastructure on offshore oil platforms, nuclear power plant, shipyards, petrochemical and other storage tanks, aircraft, buildings, bridges and railways.

The Centre for Automated and Robotic NDT has made progress in applying robots to four of these application areas. It has focused on developing wall climbing robots to provide access to large structures in hazardous environments and to deploy NDT sensors for the purposes of defect detection. These and some other related developments are described briefly here.

Figure 1 shows ROBIPM, probably the World's first climbing robot. It was first developed by the Institute for Problems in Mechanics, Moscow and modified by us to carry a six axis arm and to deploy 10 MHz ultrasonic probes to obtain C-scan defect images. The climbing robot mass is17 kg with dimensions of 409 x 300 x 100 mm. It can carry a payload of 15 kg. It uses vacuum adhesion and pneumatic cylinder/electrical motor actuation to climb with a stroke of 100 mm and change direction by rotating through a maximum of 270 degrees.

Figure 2 shows ROBSBU1, a wall climbing robot developed by the Centre to climb on flat steel walls. With a mass of 29 kg and dimensions of 740 x 540 x 150 mm, it can carry a payload of 35 kg. It uses pneumatic actuators for translation and rotational motion and vacuum suction cups for adhesion. It has a very lightweight umbilical consisting of one air tube, a twisted pair for controller communications, and one twisted pair for DC power supply.

Figure 3 shows ROBSBU2, a climbing robot that climbs on flat steel walls while carrying a 13.5 kg PUMA 260 6-axis scanning arm that deploys a 2.5MHz dry contact ultrasonic wheel probe [3]. Depth measurements suitable for the detection of corrosion thinning are performed. A PC based flaw detector displays C-scan images of the scanned material. The climbers mass is 45 kg, dimensions 740 x 700 x150 mm. It can carry a maximum payload of 35 kg. It uses vacuum suction cups for adhesion and pneumatic actuators for translation and rotation motion. The umbilical consists of one air tube, a twisted pair for controller communications, one twisted pair for DC supply, and a set of cables for the arm. The total umbilical mass is 0.5 kg/metre. Hence, the surplus payload carrying capability of the robot decreases when the robot climbs unless the umbilical is supported in some way. Our subsequent developments have always attempted to decrease the umbilical size and mass.

Figure 4 shows ROBSTEEL, a prototype robot developed by the Centre [4]. It is a self navigating vehicle for automated inspection of large plates in steel rolling mills. The robot is fully autonomous. It is designed to inspect large steel plates placed horizontally on a floor. It performs a raster line scan of a plate by detecting its edges to align itself normally to an edge before moving to the opposite edge of the plate. The robot maintains its orientation when performing a raster trajectory so that the umbilical is always to the left of the robot. The umbilical management problem is therefore made simpler. The robot deploys an array of 16 ultrasonic compression probes to detect plate defects and classify the plate into levels of acceptability to meet British Standard BS5996.

Figure 5 shows ROBNUCLEAR, a climbing robot developed by the Centre to inspect nozzle welds on 860 mm diameter pipes in the primary circuit of nuclear power plant [5, 6]. The robot can travel all the way round 45 degree nozzle welds while performing contact force ultrasonic NDT with a 23 kg 7-axis scanning arm. Adhesion to the surface is with vacuum suction cups. The climber’s motion is obtained with pneumatic actuators while the 7-axis arm is actuated with electric motors. The robot’s feet are rotated to adapt to surface curvature after each linear step.

Figure 6 shows ROBVESSEL, a similar pneumatically actuated robot that carries a 7-axis arm to perform ultrasonic inspection of welds on nuclear pressure vessels and nozzle joints [5].

Figure 7 shows ROBSPHERE, a wall climbing robot that can climb on pipes and spherical storage tanks using vacuum adhesion. The robots actuators are linear cylinders. The main innovation is a design that enables the suction feet to obtain good vacuum adhesion despite surface curvature that can occur when moving in the x or/and y direction. The four pairs of legs can be rotated independently to adapt to surface curvatures. The suction feet adapt passively to the surface through pneumatically lockable ball-and-socket joints.

Figure 8 shows ROBAIR, a climbing robot developed by the Centre to inspect rivets on aircraft wings and fuselage [7, 8]. Its mass is 20 kg and it can carry a maximum payload of 18 kg comprising of a 4-axis Cartesian scanner and NDT sensors. The embedded control system is on board the robot with control commands sent from an operator PC via a twisted pair serial communication link. Flexible ankles on all feet adjust to a range of surface curvatures. Vacuum sensors check for adequate adhesion before allowing robot motion after each walking step. The NDT of rows of hundreds of rivets is performed using ultrasonic phase arrays, ultrasonic wheel probes, eddy currents and thermography. For thermography, the scanning arm is removed and replaced by a thermography camera and heat source.

Figure 9 shows ROBTANK, a robot developed by the Centre to perform in-service inspection of oil and petrochemical storage tanks while submerged in the product [9, 10]. The robot can be inserted through 300 mm diameter manholes and operates under liquid to inspect storage tank floors and walls. It can make a transition from tank floor to wall and back to the floor. Its mass is 20 kg. The payload consists of an infrared camera, 4 ultrasonic immersion probes, 4 ultrasonic wheel probes, and two rotating bulkwave probes to give one metre diameter look-ahead capability through the floor plate.
The robot has been tested successfully performing NDT in water on the floor and walls of two storage tanks owned by Petrogal at their refinery in Sines, Portugal.
For the final tests, the NDT sensors alone were submerged in crude oil to perform NDT of test samples. The next phase of this development will be obtain intrinsic safety certification for the system. Figure 10 shows ROBTANK climbing the wall of a glass tank. Figure 11 shows the arrangement of ultrasonic probes on the underside of the robot. The four ultrasonic wheel probes are towards the top while the zero degree ultrasonic probes are towards the bottom. The two bulkwave probes are at the bottom left hand and right hand corners. These probes are lowered onto the surface and rotated to build a radar map of the floor.

Figures 12 & 15 show a conceptual drawing of ROBFPSO, an amphibious robot for the NDT of welds and corrosion on Floating Production Storage Oil tanks (FPSO) [11]. The robot is being developed as a swimming robot that can go to any given test area on a tank floor. It operates in air, sea water or in oil. The robot will be inserted through manholes in the deck of floating storage tanks. It will swim to a target area and attach itself to a wall in between structure strengthening plates. It will then climb on the wall and deploy NDT probes with a scanning arm to look at weld integrity and wall corrosion. The robot will also inspect welds on strengthening plates on the floors of the tanks. Figure 12 shows a cross section of a ship with the storage tank in the middle and ballast tanks on either side.

Figure 13 shows ROBHULL, a prototype wall-climbing robot being developed by the Centre to inspect welds on the hull of cargo container ships during their fabrication in the dry dock [12]. The climbing robot uses permanent magnetic adhesion to climb on the hulls of cargo container ships to inspect welds up to heights of 30 metres and along 200 metre lengths of horizontal weld. The robot is designed to carry payloads of 100 kg. A seven axis arm mounted on the robot deploys an ultrasonic sensor.

Figure 14 shows a seven-axis arm being developed in the Centre that is designed specifically for NDT scanning capability and portability on mobile climbing and walking robots [13]. The arm mass is 22 kg. It is designed to be robust when performing contact NDT and scanning on rigid surfaces that are not know precisely and are located remotely. Couplant tubes for the ultrasonic probes and NDT sensor cables are routed internally through the arm. The control system for the 7-axis scanning arm is currently under development.

A development currently in progress in the Centre is a project that aims to develop new and novel low cost Robot Inspection Methods for in-service Inspection of Nuclear Installation (RIMINI) [14]. RIMINI aims to overcome the drawbacks of current reactor pressure vessel inspection practices based on manual or large robots by researching and developing a submarine robot that will carry NDT sensors and will inspect the reactor pressure vessel without interfering with other operations during inspection “outage.” The Centre is developing the submarine robot. The project will eliminate the need for human intervention inside the reactor containment area that is a feature of current large robotic inspections. Phased array ultrasonic and eddy current systems will be used to examine complex structures in great detail without the need for repeated changes to the inspection probe. This will make the whole process much faster and eliminate the need for operators to enter the area during the inspection. The first prototype robot is shown in figure 16. It is a submarine wall-climbing robot that uses suction cups and wheeled motion to climb the inside wall of a pressure vessel. It positions itself over a nozzle opening so that a piggy-back robot that it carries can be inserted into the nozzle. This second robot travels 700 mm into the pipe to inspect a weld located at that position.

An European project, CROCELLS, which the Centre coordinates, aims to bring together wall climbers to create teams of climbing robots in flexible manufacturing cells for the on-site fabrication of large structures such as ships, bridges, and other large steel constructions.

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[11] European CRAFT project FPSO-INSPECT, *Non-Intrusive In-Service Inspection Robot for Condition Monitoring of Welds Inside Floating Production Storage and Off-loading (FPSO) Vessels*, 6th Framework Programme RTDD-CRAFT Proposal ref 508599

[12] Sattar T.P., Alaoui M., Chen S., Bridge B. (2001), A magnetically adhering Wall Climbing Wall Robot to Perform Continuous Welding of Long Seams and Non Destructively Test the Welds on the Hull of a Container Ship, 8th IEEE Conference on Mechatronics and Machine Vision in Practice, M2VIP2001, pp. 408-414, ISBN 962-442-191-9, Paper No. 129.

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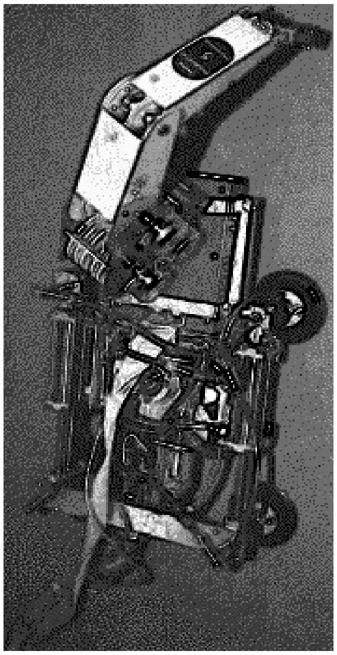

Figure 1 RobIPM
Wall-Climbing Robot

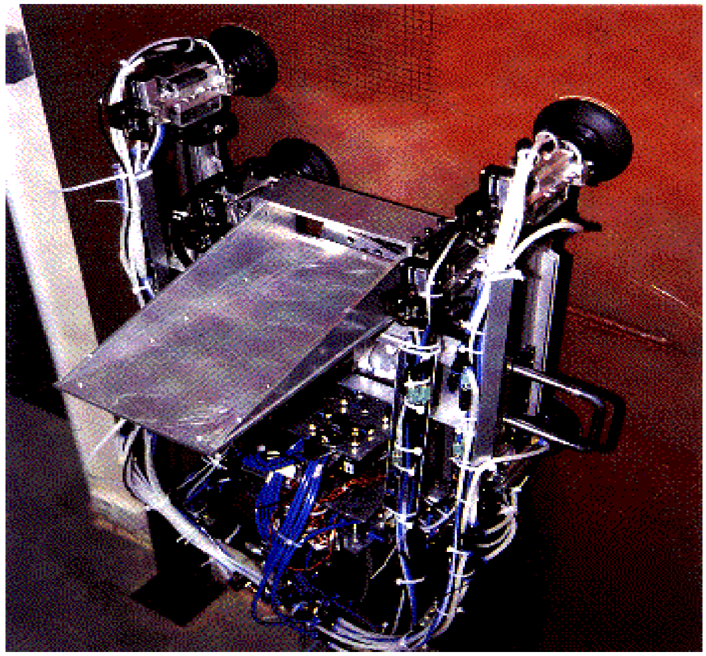

Figure 2 RobSbu1 Wall-Climbing Robot

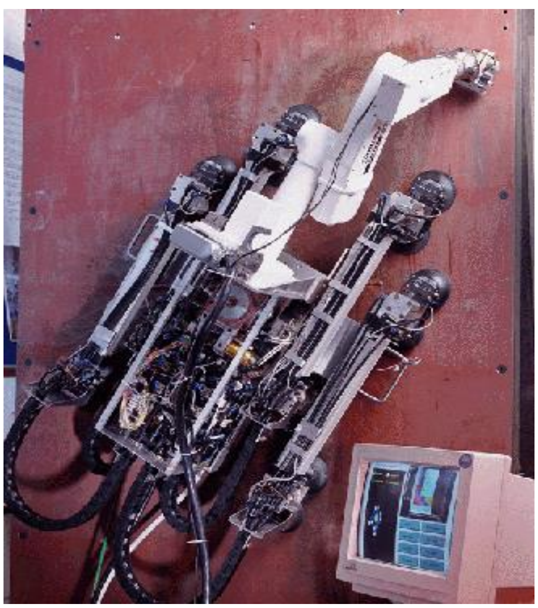

Figure 3: RobSbu2 Wall-Climbing
NDT Inspection Robot

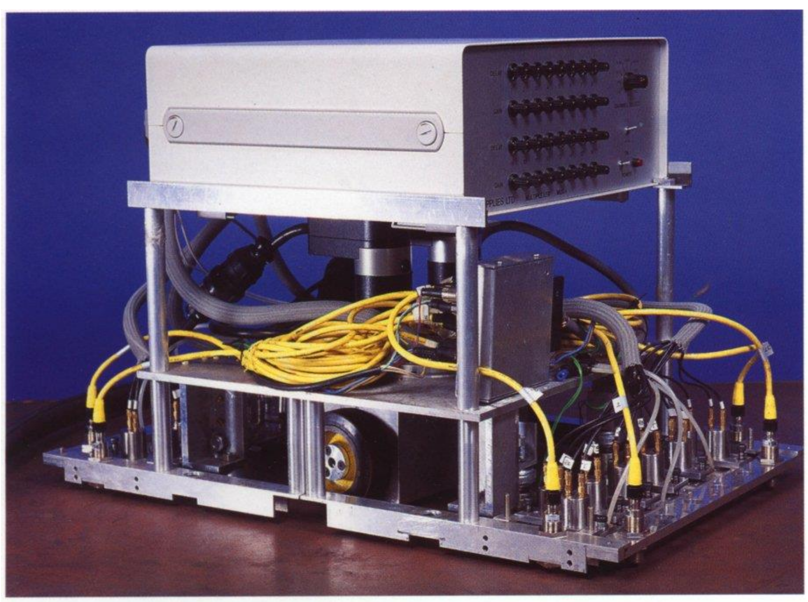

Figure 4: RobSteel Automated NDT
of large steel plates

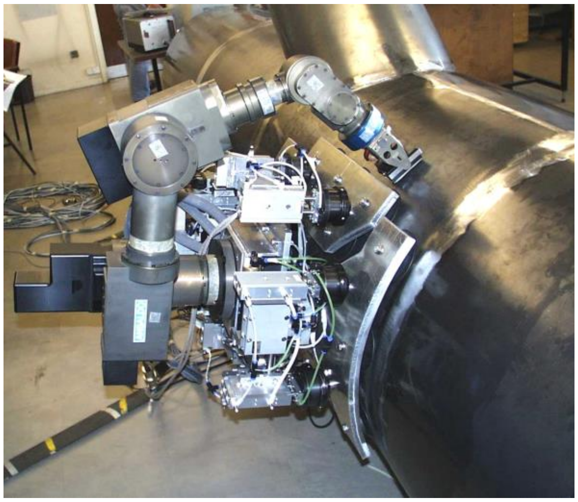

Figure 5: **RobNuclear** Climbing robot to inspect nozzle welds on 860 mm diameter pipes in nuclear power plant

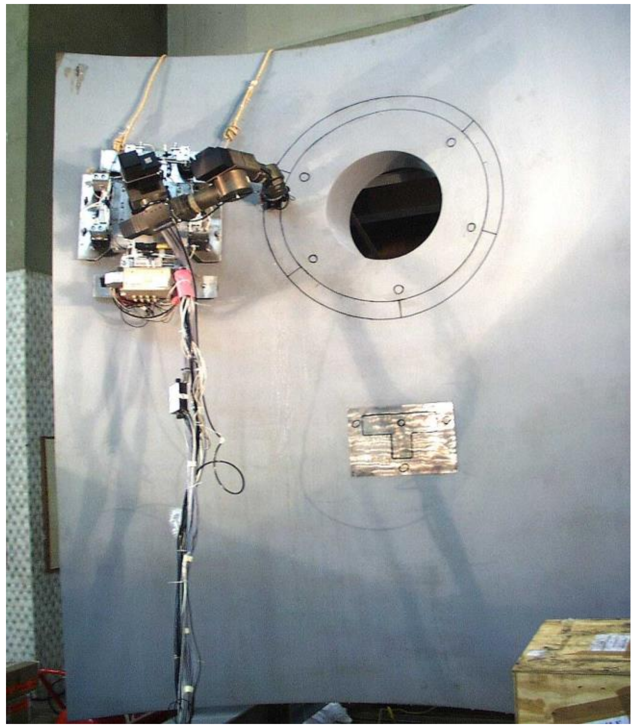

Figure 6: RobVessel Climbing robot to inspect nozzle welds on nuclear pressure vessels

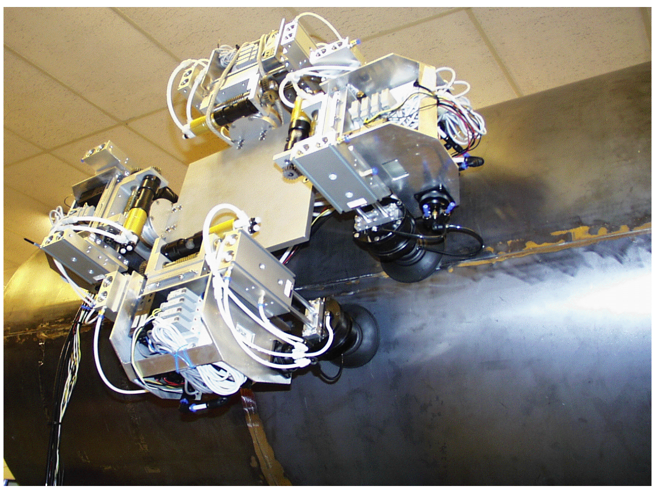

Figure 7: **RobSphere** Wall–climbing robot that can climb on spheres such as LPG storage tanks

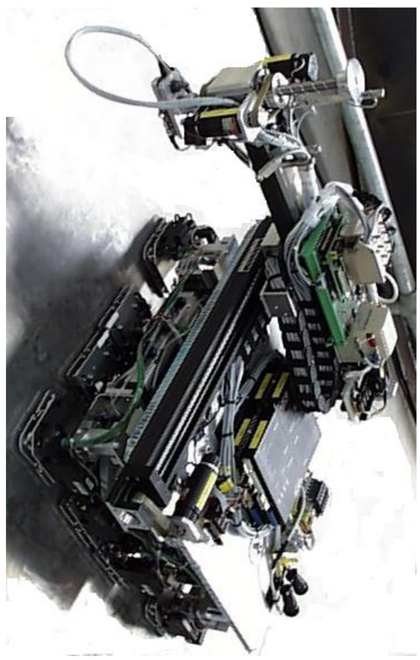

Figure 8: RobAir Wall-climbing robot for Aircraft inspection

Figure 9: **ROBTANK** Floor And Wall-Climbing Robot For The Inspection Of Petrochemical Storage Tanks

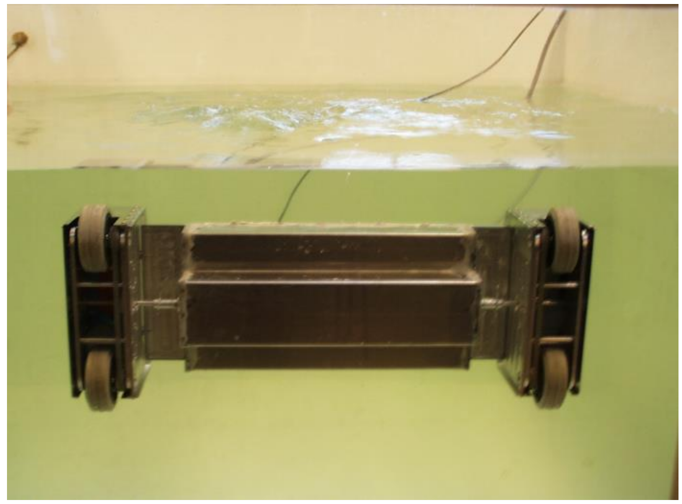

Figure 10: **ROBTANK** Climbing On The Glass Wall Of A Laboratory Tank

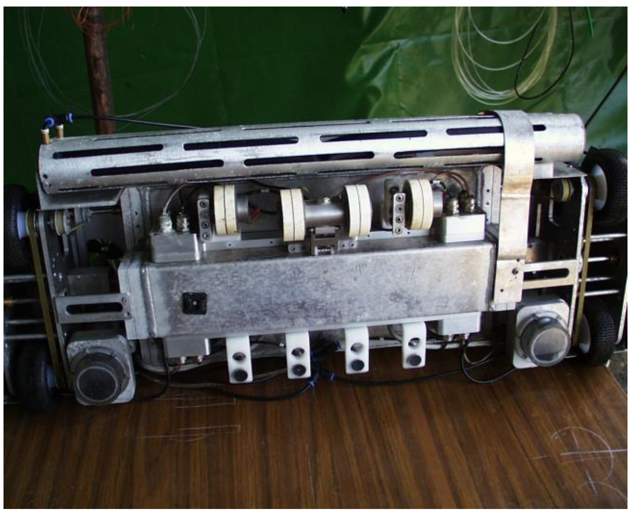

Figure 11: NDT Sensors On The Underside Of the **ROBTANK** Robot

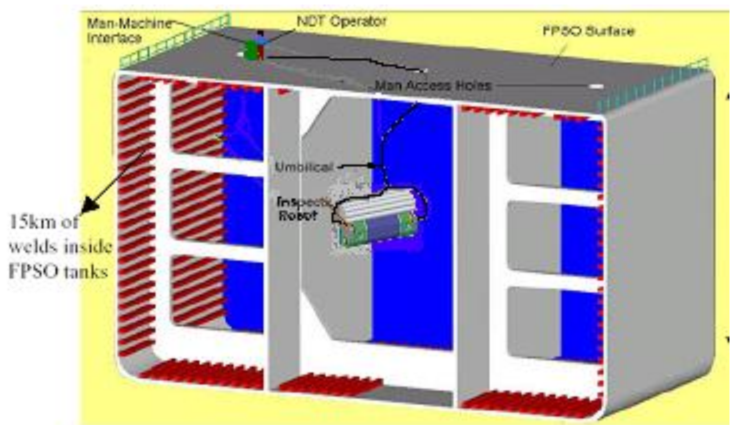

Figure 12: **ROBFPSO** Swimming and Wall-Climbing Robot For NDT of Floating Production Storage Oil Tanks

Figure 13: **ROBHULL** Robot For The NDT Of Welds On Ship Hulls

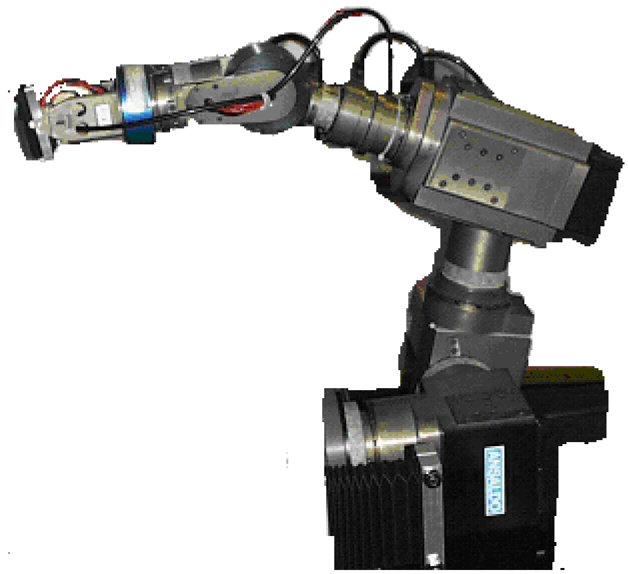

Figure 14: Control Of 7-Axis NDT Scanning Arm Designed Specifically For Mobile and Climbing Robots

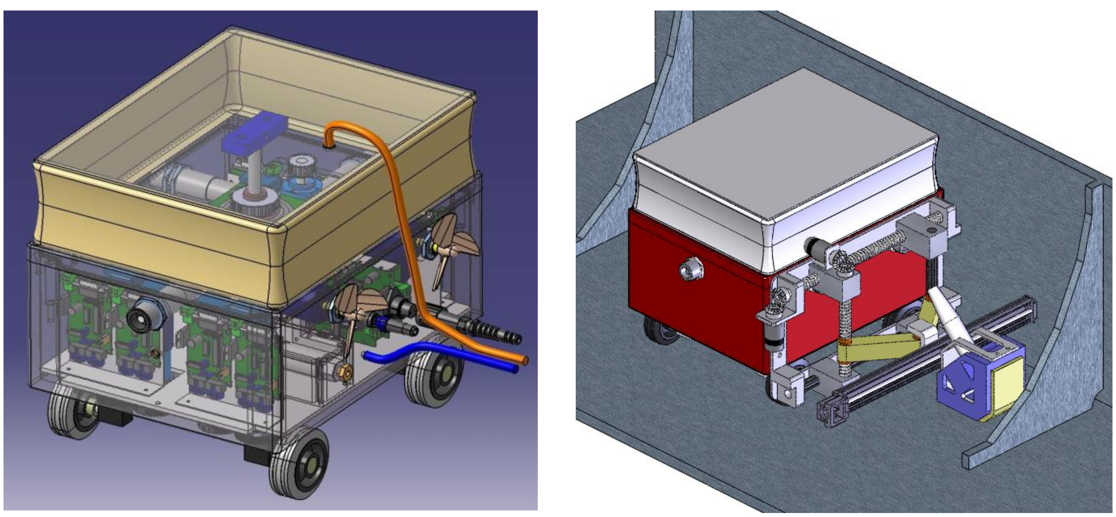

Figure 15: Left, Amphibious FPSO Robot with buoyancy tank and all electronics in a single enclosure. Right, Scanning arm and ACFM probe opposite a strengthening plate

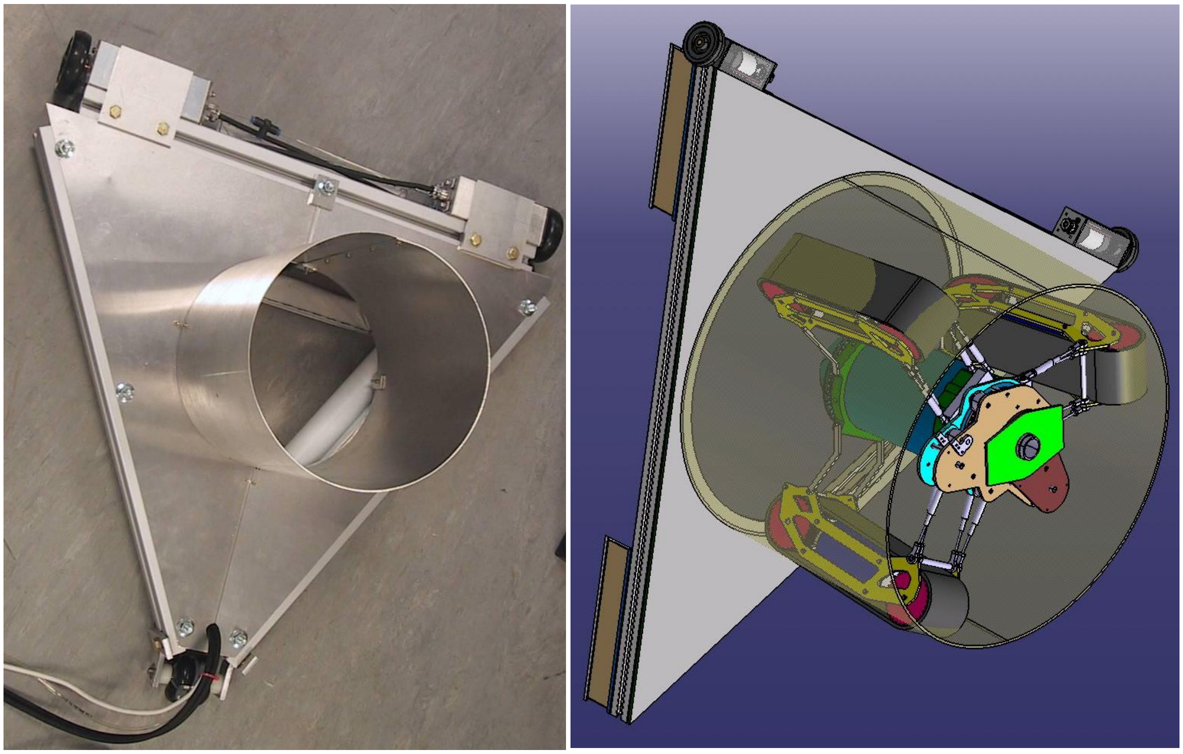

Figure 16: Prototype Wall Climbing Robot on the left. On the right is a concept drawing of pipe crawler inside its carriage tube.