Mobile wall climbing and swimming robots to inspect aircraft, storage tanks, pressure vessels and large infrastructure

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Abstract- Non-destructive testing (NDT) of very large critical infrastructure that may be located in hazardous environments, poses the problem of first gaining access to the test site before the testing can be performed. Providing access usually constitutes the major part of the cost and time spent on the testing. Hence, a great deal of effort has been directed recently at developing mobile robotics that transports a payload of NDT sensors to the test site, preferably without taking the structure out of service.

The paper describes a number of mobile, wall climbing, swimming and pipe climbing robots that have been designed by the authors to perform the non-destructive internal inspection of petrochemical storage tanks and nuclear pressure vessels, the inspection of the wings/fuselage of aircraft and the blades on wind turbines by climbing on their external surfaces.

I. Wall climbing and swimming robots for non-destructive testing

Application areas for automated and robotic non-destructive testing (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. Earlier progress in applying robots to these application areas is reported in [1, 2, 3]. Research and development by the Centre for Automated and Robotic NDT has focused on designing and prototyping wall climbing robots to provide access to large structures in hazardous environments and to deploy NDT sensors for the purposes of defect detection. Inspection of these structures requires that the robots should be able to climb on vertical surfaces, make transitions between surfaces, operate in liquids, deploy a range of NDT sensors with sufficient precision to detect and size defects, acquire defect data and make it available to an NDT inspector for analysis, and be intrinsically safe when operating in explosive and flammable environments.

Some recent developments are described briefly in the following sections..

A. Non Destructive Testing (NDT) of long weld seams on large structures

A European project, called 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 [4,5,6]. Figure 1, conceptual drawing on the right, shows the team of robots comprising of a cleaning robot, a welding robot, a support robot that carries the feeder wire for the welder, a welding robot and an NDT climbing robot. The prototype NDT robot is shown on the left.

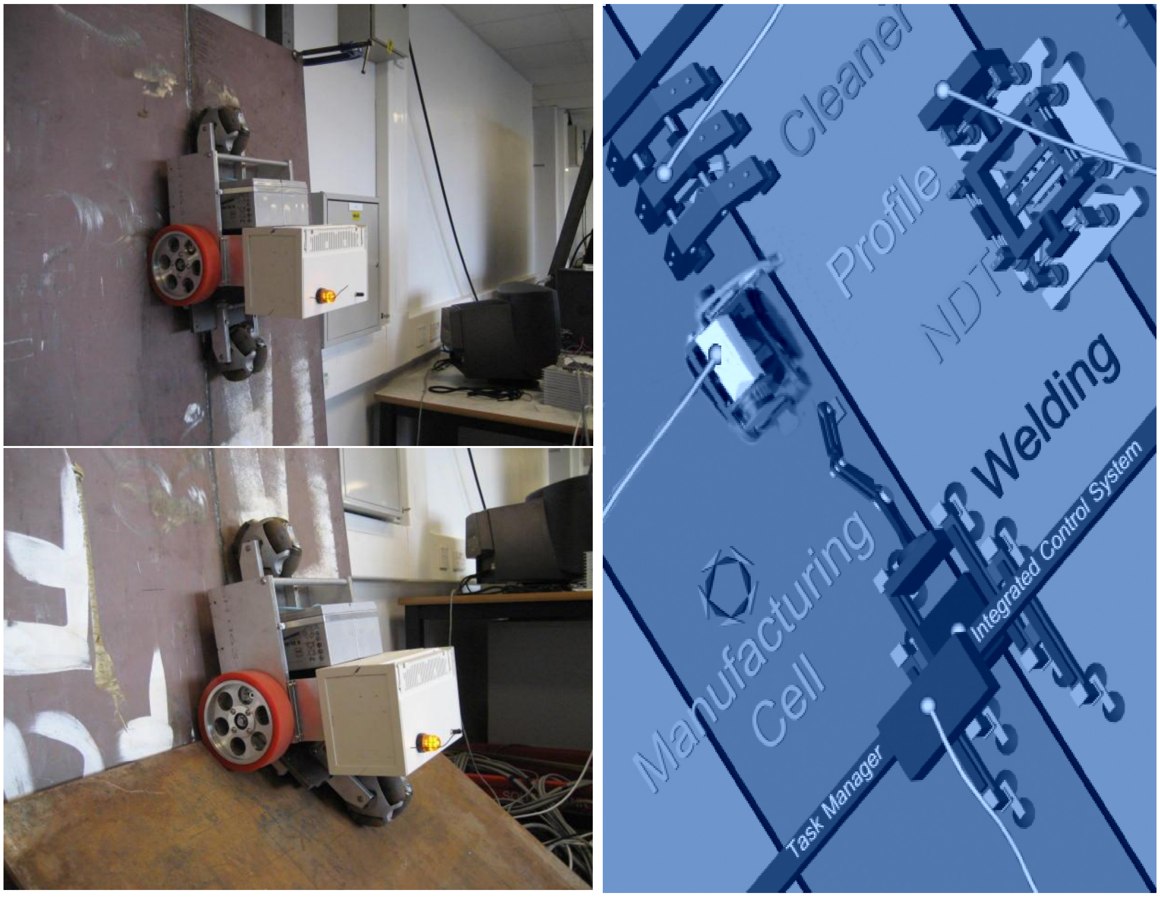


Figure 1. Wall climbing and surface changing robot that uses permanent magnet adhesion. No cables, wireless control and NDT data acquisition.

B. NDT of wind turbine blades

Inspection of offshore wind turbine blades poses tremendous problems of access, danger to human operatives and large costs of bringing the blades back for testing. For these reasons, robotic in-situ blade inspection of offshore wind turbines with micro/nano focus computed axial X ray tomography (MNCAT) has been identified as the optimal if not the only solution for identification of safety critical defects in the thickest blade sections. The weight of such an inspection system is very high, typically 200kg and typical cross sectional scanner dimensions of 1m x 2 m to encircle as blade, clearly involve very high destabilizing moments to be countered by the deployment robot. The solution is a modular climbing ring robot completely encircling a turbine tower, typically 3 meter in diameter. Because of the size and thus development costs of such a huge robot the optimal design path is to prototype a small scale model. First results on such a model are described and from its performance the load carrying capabilities of a full scale version are computed and the scale model can then be refined by 'reverse engineering' to guarantee that a full scale construction is able to meet requirements.

Figure 2 shows a novel ‘ring’ climbing robot with a payload capability allowing it to climb around the cylindrical tower and scan the blades in situ with a Cartesian scanning arm. The key innovation is that the adhesive forces between the robot and climbing surface a provided entirely by mechanical means rather than by using the usual methods of vacuum suction, air vortex or magnetic force, making the system much cheaper and easier to manipulate.

The prototype has three modules which are completely identical and can be easily joined together to climb on any circumferential tube. The tower has a tapering radius. The robot is placed around the tower and it uses spring forces to grip it. Active force control could also be used to adapt to changing radius but this method has not been used here.

Each module uses two motors, one for the drive motion and the other to turn the angle of the wheel so that the robot climbing trajectory is spiral. The robot has the capability to face the driver wheels in different angles which means that the robot can either climb along the tube, see figure 10 (column a), or with a certain pitch angle it can spiral around the tube, figure 10 (column b), or if the wheel is turned through 90 degrees then the robot will not climb but it will rotate around the tube in the same spot, figure 10 (column c).
The prototype has been built to a linear scale of 1:10 (for both the robot and test pipe) and tested successfully performing the three types of motion i.e. up/down, spiral, and rotation on the spot. The robot weight is 3kg , the payload capacity is 2kg with a safety factor of 2 and maximum speeds of climbing and circumferential motions are 10m/min. In the full scale model the cross sectional area over which adhesive forces between the wheels and turbine tower could be developed would increase by a factor of 100 (assuming the wheel widths and diameters to be scaled up by a factor of 10 and the payload capacity can thus be potentially increases in the same proportion to about 200kg, the target figure. However, if necessary, adhesion forces can always be augmented in the full scale design by the inclusion of a number of rare earth magnet arrays.

The climber will carry a scanner robot that will take several number of X-ray pictures that will be analysed by computer tomography.

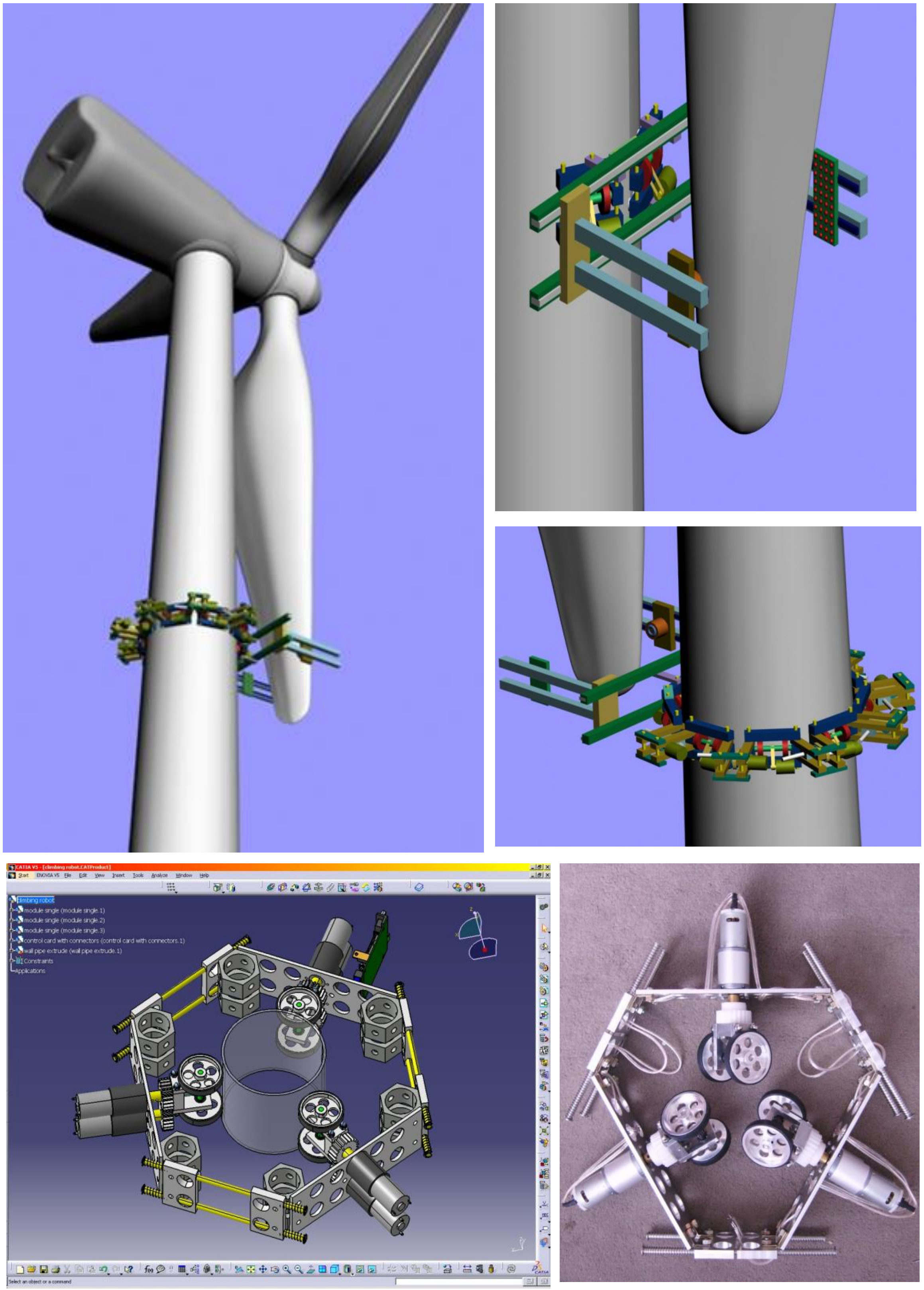
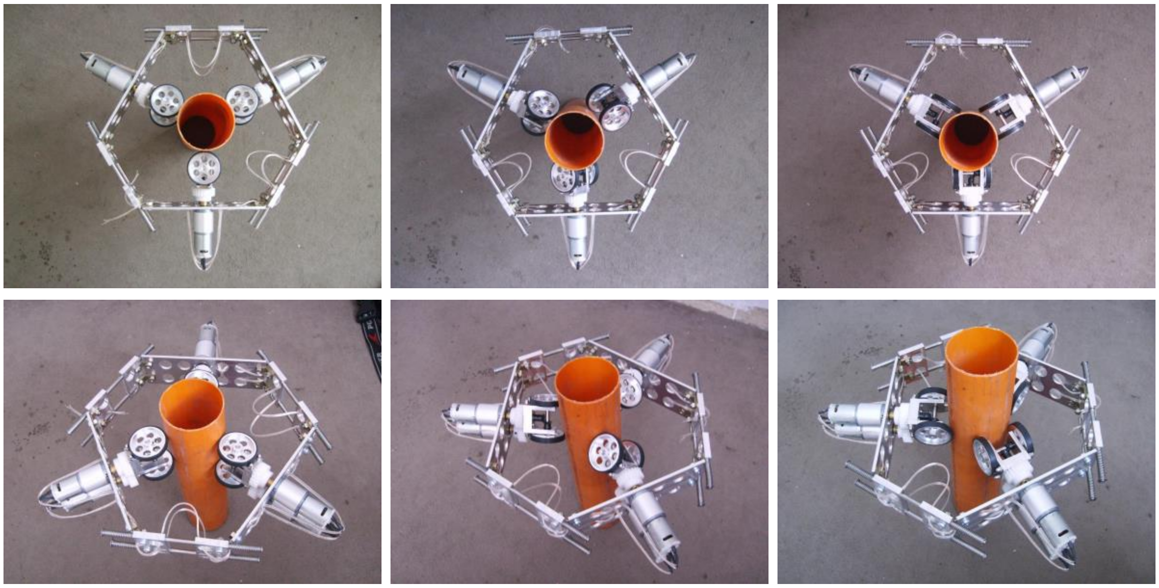


Figure 2. Modular ring robot, scaled prototype, climbs on the column of a wind turbine to perform in-situ inspection of blades with X-ray tomography.



A B C

Figure 3. Wind turbine climbing robot. Column A wheel arrangement for rotation around the tube at the same spot, B shows spiralling motion, C shows straight up-down motion

C. NDT of the floors and walls of petrochemical storage tanks

Figure 4 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.

The paper presents the test results of a swimming and floor moving robot inspection system to test welds located inside a floating production storage oil tank (FPSO tank) [1]. Currently these welds are inspected manually by first emptying and cleaning the tank. This is a time consuming and expensive operation that requires operators to enter a hazardous environment. Significant cost reductions would be made if the inspection could be automated so that the tank is either emptied so that only two to three centimetres of oil remain on the tank floor or preferably if the robot can perform the inspection in a full tank. In the first case the robot would operate in air and an explosive environment but would eliminate the need to swim the robot through a very complicated maze of partitioning walls and rows of strengthening plates that occur every 700-900 mm. In the latter case the robot would swim to a strengthening plate and operate under oil thereby eliminating the need to empty the tank. The FPSO inspection task and suitable Non-destructive Testing methods are reported in [2-3].

Figure 1 shows the amphibious robot prototype that is designed to operate in air as well as submerged in water (at this stage) though eventually it has been made intrinsically safe to operate in crude oil (API 20 to 40). It consists of a buoyancy tank on top that adjusts its buoyancy around neutral by controlling of mass. A depth sensor provides the feedback to regulate the depth at which the robot is required to maintain its position anywhere in the tank. Thrusters control the horizontal motion of the swimming robot.

The navigation system into the tank and the robot's orientation are controlled by four ultrasonic sensors operating at 10 KHz and a rotating ultrasonic sensor at 5 MHz profile the surrounding strengthening plates and tank walls. These sensors are used to align the robot and to guide it autonomously along welds between the floor and strengthening plates and the toe ends of the plates. The cartesian scanner shown in figure 1 carrying an ACFM probe scans the welds after the robot has been positioned correctly.

Robot trajectory in a constrained space for precise weld following around plates and side walls requires motion that is straight-line along welds, 90º rotation to present the scanner arm correctly when going from a plate to a side-wall and back onto the next plate. Special mechanisms have been designed to rotate all four wheels through turning angles between ± 180º and to independently control the speeds of all four wheels.

Conclusion

The paper will describe and demonstrate the performance of the amphibious inspection robot operating in water and in air. Final NDT results obtained with ultrasonic and ACFM techniques applied to a mock-up of FPSO strengthening plates will be presented. The paper will discuss features of the design that will enable further development for operation in oil and explosive environments.

Figure 4. RobTank wall climbing and floor moving robot for the NDT of petrochemical storage tanks. Robot being inserted through manhole, climbing walls and on tank floor

D. NDT of rivets on aircraft fuselage and wings

Figure 5 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.

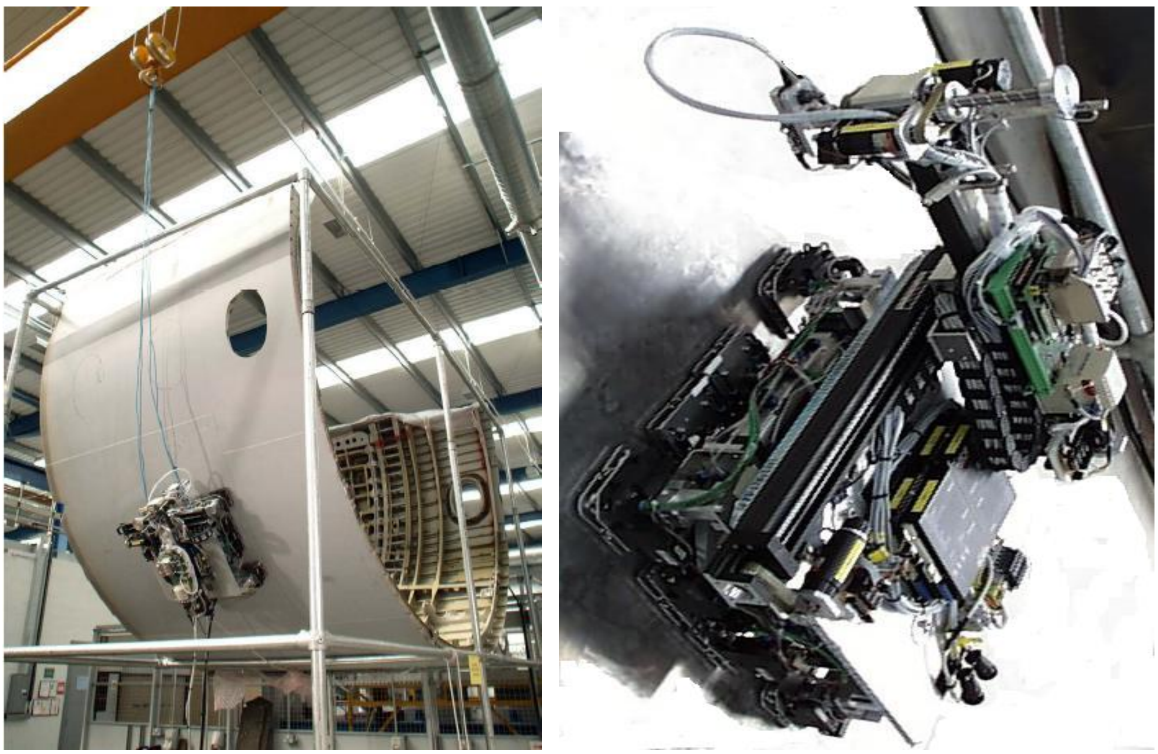


Figure 5. RobAir climbing robot to inspect rows of rivets on aircraft wings and fuselage

E. NDT of circumferential welds inside nozzles on nuclear pressure vessels

A project to develop new and novel low cost Robot Inspection Methods for Inspection of Nuclear Installation (RIMINI) has developed the underwater climbing robot shown in figure 6. 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 has developed the submarine robot. The robot aims to eliminate the need for human intervention inside the reactor containment area that is a feature of current large robotic inspections. 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.

Phased array ultrasonic and eddy current systems are used to examine complex structures in great detail without the need for repeated changes to the inspection probe.

The wall climbing robot developed in this work is an underwater robot that moves on the wall of a PV from one nozzle to another to position a scanning robot over a nozzle opening. It can be lowered into a pressure vessel (PV) by one or two operators or by an overhead crane.

The final robot design and construction is shown in figure 2 on the mock-up of a pressure vessel.

It uses vacuum adhesion to climb on the internal walls of a pressure vessel while submerged in water. The robot is teleoperated and positioned over a nozzle (760mm diameter at its opening but tapers down to 540mm at a distance of 700mm from the wall). The wall climber carries another pipe crawling robot on its back inside a 600 mm tube. After positioning the wall climber accurately over the nozzle, the pipe crawler makes a transition into the nozzle and travels to the internal weld. It adapts its size to the pipe diameter during this motion. It then locates the circumferential weld and scans it.

A triangular configuration of three omni wheels and three motors enables straight line motion in any direction thereby easing the positioning of the robot over a nozzle.
The climber design is modular and symmetrical so that any of the identical robot links and brackets that make up the body of the robot are interchangeable. In addition, all three motors, three suction cups, and three pumps are identical and interchangeable so that the robot can be assembled/disassembled very quickly to enable its transportation from site to site. A major consideration in the design is the radiation hardening of motors, sensors and umbilical cable as well as the selection of materials to prevent chemical interaction with the water in the vessel and its possible contamination by the inspection system. Another important consideration is the assured retrieval of the robot in case of breakdown.
The first prototype robot is a half size of the final working prototype (see figure 7) and is designed to provide high manoeuvrability to allow easy adjustment of the robots position over a nozzle. This prototype robot adheres to the wall of a tank (pressure vessel) by using sliding suction cups (this technique will be explained further). The design uses 3 standard DC motors for motion control of the climbing robot. The motors are housed in a sealed and air pressurised aluminium 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.
The design doesn’t have any electronics on-board to get a prototype close to the real environment. There are no shaft encoders or position/velocity sensors mounted on the motors; also they are controlled by PWM Servo drives which are placed out of the pressure vessel. Cable length from servo drives to motors is about 30 m.

Equal distributions of weight to the wheel axels ensure that each wheel must overcome the same amount of minimal friction as the others. Another advantage of a triangular base is the structural rigidity gained from the geometry of a triangle; the triangles vertices are fixed, maintaining three 60 degree angles, and therefore creates a rigid structure.

Straight line motion, diagonally or forward / backward depends on the ability of the control system to rotate two wheels with equal speeds and at the same time.
Using omni-wheels at the corners of an equilateral triangular where these are able to roll smoothly in any direction, the robot is free to move with three degrees of freedom. Given the four basic directions shown in figure 5, an infinite number of combinations and therefore motions are possible.
Other robot motion can be obtained by rotating the individual wheels at different angular rates. The resultant wheel velocities produce both linear and angular motion of the robot platform; the basic analysis of this motion can be seen in the figure 7.
Figure 6 shows the physical analysis of the robot’s wheels; each of the 3 wheels has a rotational and translational (x and y) velocity. These combinations of specific velocities ensure a particular translational and rotational velocity of the robot.

Lab and field trials of the whole system were done in water diving tanks. The climbing robot was tested extensively without the scanner arm as the latter was not ready for testing by this time.. The scanner was demonstrated being carried by the climber in a water tank. Damage to the scanner electronics due to water leakage prevented further tests on transitioning of the robot into the nozzle but tests to keep the robot parked on the nozzle when the scanner leaves the climber were done by using a dummy load (carrying it to a given location, putting down suction cups to attach the climber to the wall and then removing the load to test the ability of the system to keep the climber stationary despite the large positive buoyancy that results).

The robot was able to climb easily on tank walls of the specified diameter, despite walls that were quite dirty (covered with algae) while carrying the scanner robot that exceeded the specification mass. Operating nuclear pressure vessels are very clean with a uniform radius of curvature and hence the robot will have no problems on such surfaces.

The robot will not need radiation hardening. Only the canvas used to construct the suction cups and the polypropylene buoyancy tubes will need to be replaced when the robot operates in a nuclear pressure vessel as all the other parts are constructed from stainless steel, anodized aluminium, nylon, rubber or polyamide.

Positioning of the wall climber is done by teleoperating the robot visually into position. Shaft encoders and other electronic positioning sensors were deliberately not used in the climbing robot design to develop a robust robot that could work for long periods in a radiation environment. In the final stages of positioning, the intention was to use the vision system on-board the scanner robot to make small adjustments to the climbing vehicle's position to enable the scanner robot to make a transition from the climber into the nozzle. This final adjustment was not tested because the scanner robot developed a fault during the trials and could not be repaired in time.

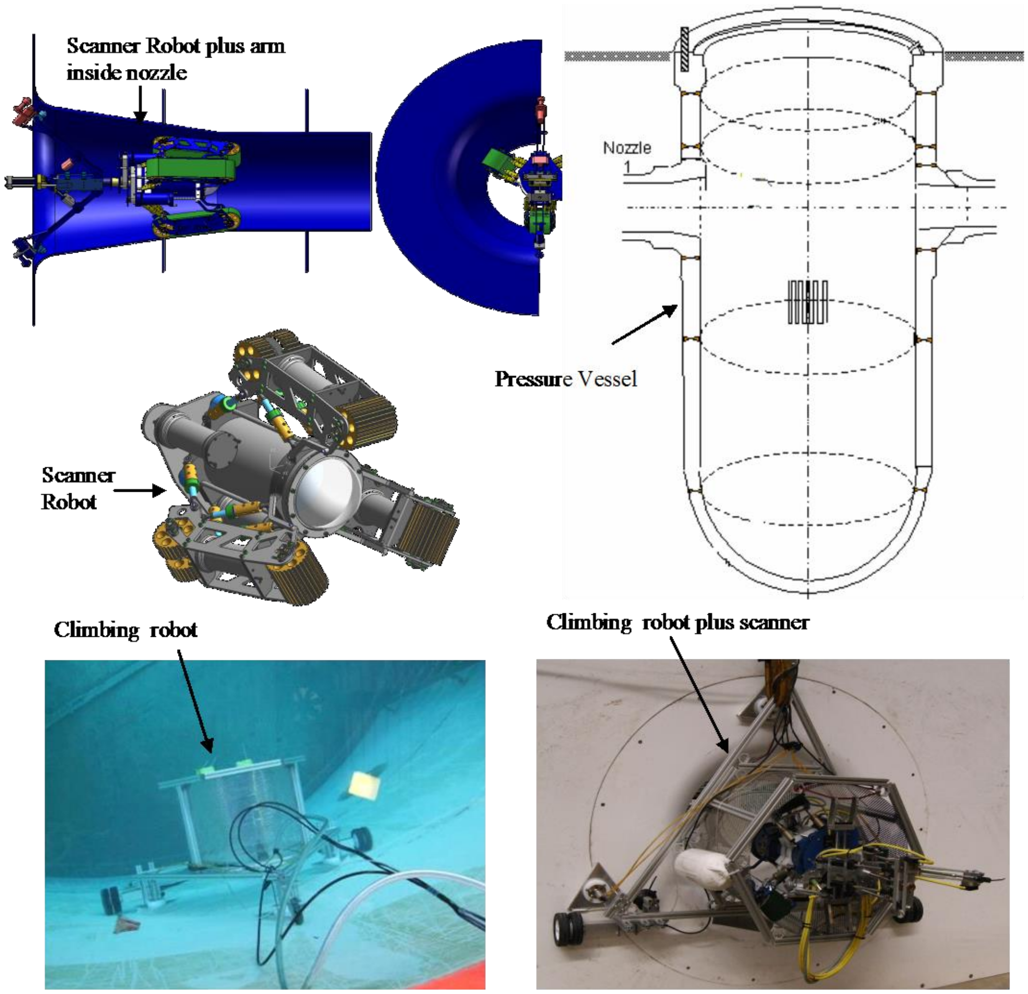


Figure 6. RIMINI wall climbing and pipe crawling robot for the NDT of welds inside pressure vessel nozzles

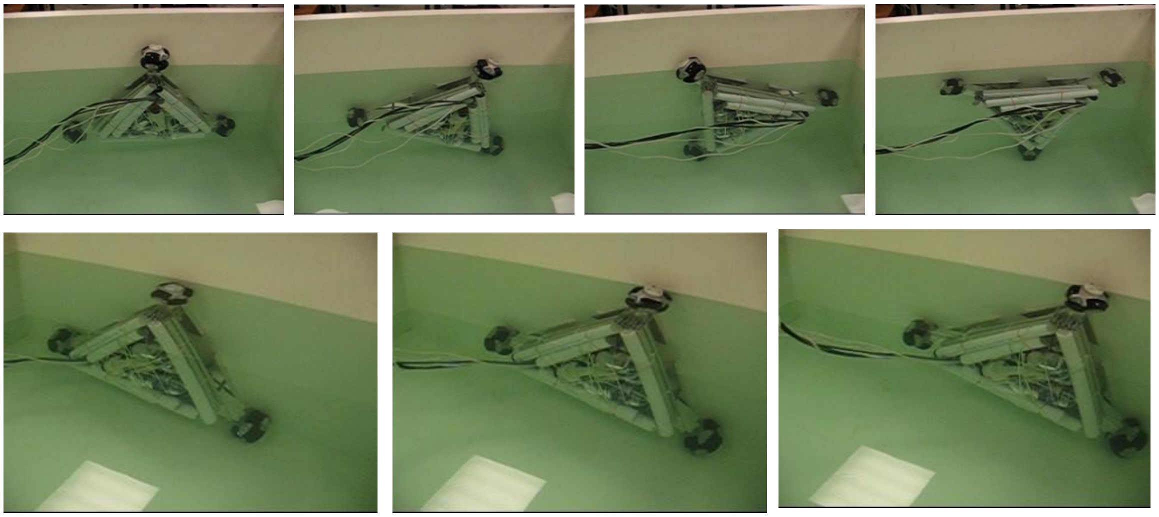


Figure 7. RIMINI wall climbing robot: Top row shows rotation of the robot at the same spot. Bottom row shows movement of the robot along the wall.

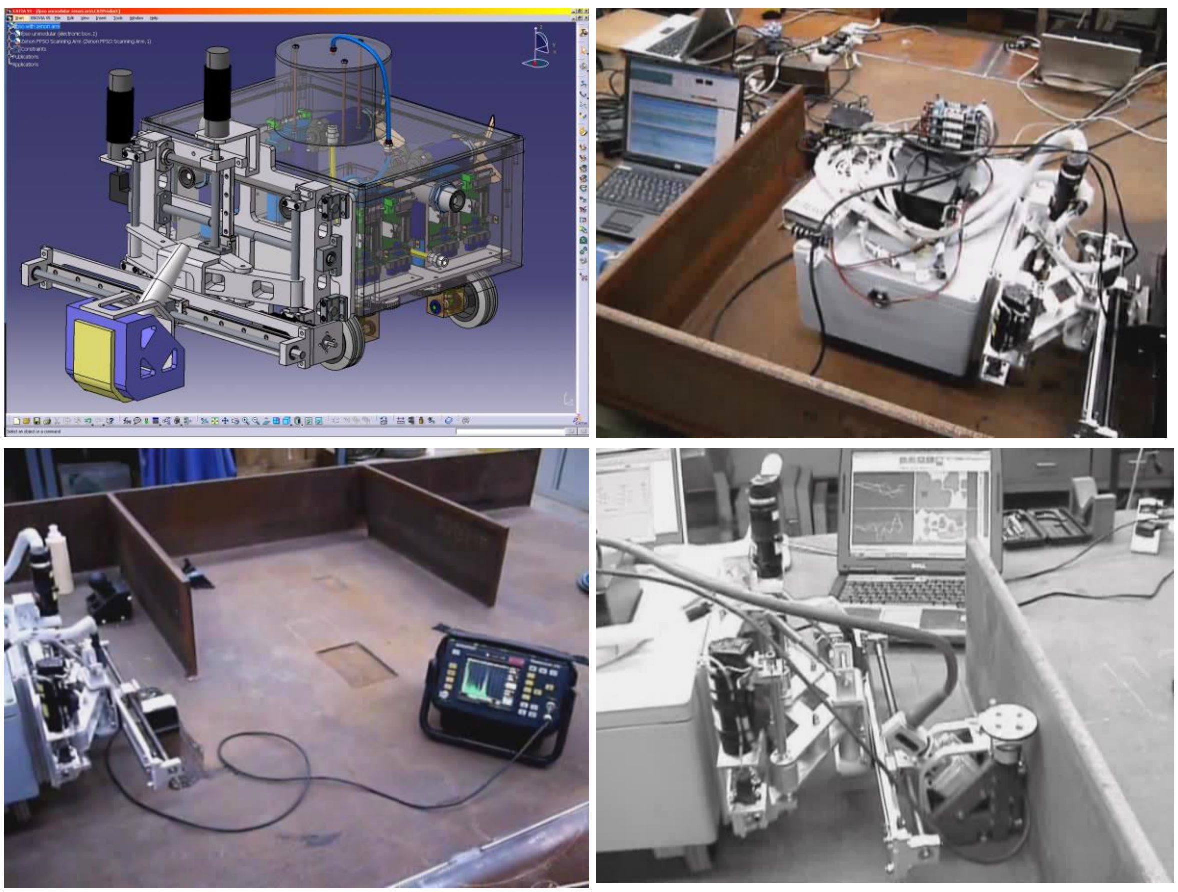


Figure 8. FPSO amphibious robot shown performing NDT with ACFM arrays, and ultrasonic creep waves. Robot swims in liquids and uses wheeled motion on floors (while submerged or in air) to follow welds on ship stiffener plates

F. NDT of Floating Production Storage Oil (FPSO) tanks

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.

The paper presents the test results of a swimming and floor moving robot inspection system to test welds located inside a floating production storage oil tank (FPSO tank) [1]. Currently these welds are inspected manually by first emptying and cleaning the tank. This is a time consuming and expensive operation that requires operators to enter a hazardous environment. Significant cost reductions would be made if the inspection could be automated so that the tank is either emptied so that only two to three centimetres of oil remain on the tank floor or preferably if the robot can perform the inspection in a full tank. In the first case the robot would operate in air and an explosive environment but would eliminate the need to swim the robot through a very complicated maze of partitioning walls and rows of strengthening plates that occur every 700-900 mm. In the latter case the robot would swim to a strengthening plate and operate under oil thereby eliminating the need to empty the tank. The FPSO inspection task and suitable Non-destructive Testing methods are reported in [2-3].

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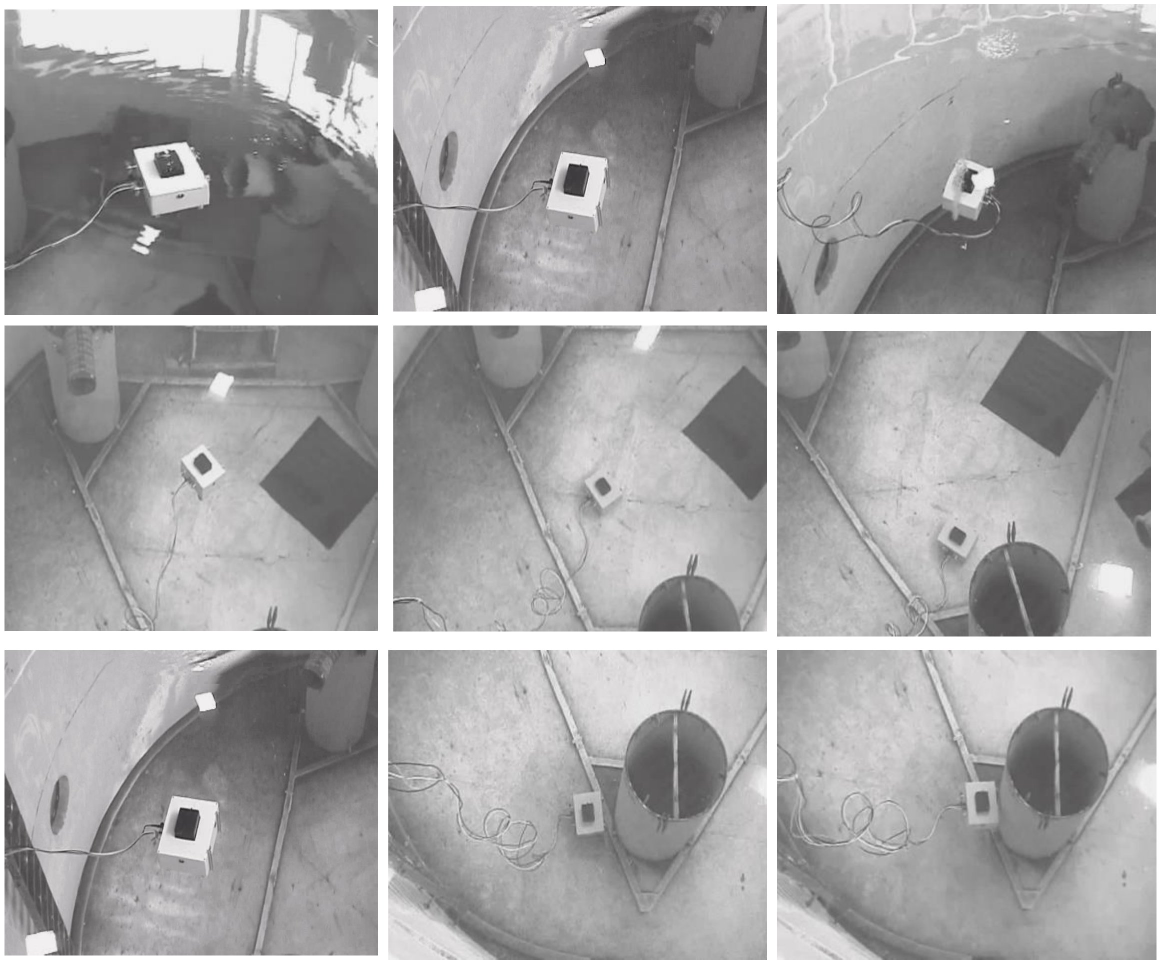

Figure 9. FPSO swimming robot in a water tank. Top row- vertical motion by buoyancy control; middle row- swimming with two thrusters and descent to the floor where robot moves around on the floor; bottom row- swimming motion to obtain wall inspection.

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