Robotic Inspection Solutions for Petrochemical Pressure Vessels, developed and tested in the PETROBOT project

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Abstract. Pressure vessels used in the petrochemical industry need to be regularly inspected. Currently this is done manually by people working inside the vessels, which is a very time consuming operation in a potentially hazardous work environment. Robotic technology is now sufficiently developed to be used as a platform to perform the inspections using established techniques. The EU funded PETROBOT project aims to bring together inspection methods and remote delivery to reduce risks and cost involved in inspection of pressure vessels.

PETROBOT brings together the complete value chain, from robot and inspection technology providers to inspection service providers and end-users. PETROBOT is an industry run development project where the aim is to develop and demonstrate robotized inspection equipment at a high TRL level. Dekra Industrial participates both as inspection technology provider and as inspection service provider. The inspection systems will be tested in real installations of the participating end users.

For inspection of pressure vessels, three different robots have been developed. Two reacrawlers, developed by Alstom Inspection Robotics, the third is a so called snake-arm robot, developed by OC Robotics. The three robot types complement each other to enable robotised inspection capabilities in a variety of pressure vessel designs. The robots will be able to carry a payload consisting of inspection tools: a camera for visual inspection, structured white light for profilometry of indications, an ultrasonic transducer or an eddy current transducer. The main, and most versatile inspection method, is visual testing. The other methods will be applied when an initial visual inspection identifies a need for more specific inspections. The results show that at least a similar detectability as for the conventional inspections can be achieved. This novel inspection system will be tested on artificial defects and proven in real pressure vessels during the final stages of the PETROBOT project.
**Introduction**

Companies in the petrochemical industry own many assets used for processing, storage and transport of (oil and gas) products. Assets include items like piping, pressure vessels and Aboveground Storage Tanks (AST). These assets are complex and made of multiple components that require inspection or non-destructive testing (NDT) at regular intervals. The majority of these inspections are conducted by human inspectors and preparation for human entry is lengthy and complex to facilitate.

Preparation for inspection commences with the asset being isolated from the rest of the plant, empties, cleaned, then made safe for human entry. This process can take several days and may affect operational efficiency of the plant. Scaffolding is erected in order to provide access to the object or area to be inspected. Thorough cleaning, degassing and constant air quality monitoring are required to ensure health and safety standards are met.

Once preparation is complete, human inspectors are under pressure to complete inspection and NDT tasks as quickly as possible to minimise asset downtime. This time pressure adds to the complex challenge of working in a confined space in hot and humid conditions, all the while wearing heavy and uncomfortable protective equipment.

Putting the asset back into service also required significant effort and time. Even simple inspections can require the asset to be offline for a significant amount of time due to preparation and reintegration works. The preparation for the inspection process is by far the most expensive aspect of an inspection, with additional cost occurring if the asset is out of production. An example of robotic inspection was estimated that up to 30% saving were made by using robotic inspection methods [3].

In terms of human safety, petrochemical plants are inherently hazardous environments. From time to time accidents do occur that are related to human entry of confined spaces. Historic attempts [4] to reduce human entry have shown the gap to be too large between available remote inspection equipment and the inspection requirements. Today, rapidly deployable robotic technologies are sufficiently developed to be used a platform for established inspection techniques. As a result, major oil and gas industry players are exploring robotic use to meet their targets of minimising man entry [5].

**Objectives**

The objective of the PETROBOT project is to deploy robotic technology to minimize the exposure of maintenance- and inspection personnel to potentially hazardous conditions by eliminating the need for them to enter the components to be inspected.
The project consortium is designed to minimize the time to market the developed inspection solutions by mobilizing the complete value chain, from robot and inspection technology providers, inspection service companies to end users.

To our knowledge, this is the first time that robotic manipulators have been combined with inspection tools to create versatile robotic inspection systems with at least the same detectability requirements as human inspectors have, certainly on an industrial level at high TRL.

**Developed inspection systems**

The PETROBOT project is integrating existing petrochemical inspection techniques and tools with mature industrial robot technologies that have a track record within other industries. Development of the robots has been within the constraints of existing pressure vessels and design for operation in the hazardous environments that petrochemical plants pose. Inspection tool development has aimed to match the quality of results from existing manual techniques, and on size reduction for mounting on the robots.

**Snake-arm robot**

The SNAKE arm robot is developed by the UK company OC Robotics. In general, the SNAKE-arm robots consist of a set of links, connected at joints, and an actuator pack. The actuator pack consists of motor drives and electronics that control a set of ropes. These ropes travel from the motor in the actuator pack to a certain joint in the arm, through the interior of the arm. SNAKE-arms can be made in 3D- moveable versions, called spatial arms, or 2D-moveable versions, called planar arms. For space and weight reasons, a planar arm was developed for PETROBOT, seen in figure 2.

![PETROBOT SNAKE-arm](image)

**Fig. 2. PETROBOT SNAKE-arm.**

The PETROBOT SNAKE arm is a 4m long planar arm, where the links are made of carbon fibre. The outer end of the arm consists of a wrist made of four segments, shown in figure 3. The last segment incorporates navigation cameras, lights and attachment for the inspection tools. In figure 3 one can see one of the available tools, the Gocator, mounted. As each segment can be turned ±90° the wrist contributes to a very high degree of flexibility and reach of the SNAKE.
Fig. 3. Wrist part of the SNAKE with Gocator mounted.

The SNAKE is navigated using a game-pad. The navigation software allows for a nose following mode, which means that the operator can focus on the position and direction of the nose and tool, the software will make sure that the rest of the arm follows the same path.

It has been designed with operation in ATEX Zone 1 (Ex IIC p IIA T2) (OJ, 1994). For PETROBOT, the SNAKE has been designed to carry an inspection camera, the Gocator, an eddy current probe and a phased array ultrasonic probe.

BIKE inspection robot

The BIKE robot is developed by Alstom Inspection Robotics (AIR). The BIKE is a small, very versatile robot using magnetic wheels for motion. This means that it is only feasible to use in ferrous vessels. The robot is shown in figure 4.

Fig. 4. BIKE robot.

The BIKE has been designed for maximum manoeuvrability, and to be able to pass obstacles. It uses four independently driven magnetic wheels aligned in two rows that allow the robot to climb vertical walls, follow circumferential paths, pass convex and concave 90-degree corners. It requires only limited space as it can turn on the spot around the rear wheels. Figure 5 shows the BIKE passing a corner.

Fig. 5. BIKE robot passing a corner.
For PETROBOT, the BIKE has been designed to carry a lightweight inspection camera (Visatec VT34), the Gocator and an eddy current probe.

FAST inspection robot

The FAST robot is also developed by Alstom Inspection Robotics (AIR). It is as the BIKE equipped with magnetic wheels, and thus applicable on ferritic surfaces. Figure 6 shows the FAST, as developed for PETROBOT.

![Fig. 6. FAST robot with inspection camera mounted.](image)

The vehicle is modular, enabling different wheel and body sections to be attached to each other. Further the inspection and tool area is modular enabling easy exchange of NDT inspection tools. Services, control and inspection data are sent and received via the umbilical that connects the operator to the crawler robot. Of the three robots developed within PETROBOT, FAST can carry the largest payload. As the ground clearance is limited, FAST can be used in objects with smooth surfaces with minor obstacles.

FAST has been provided with advanced navigation aids for safe operation. Leading edge mobile robotic navigation capabilities, simultaneous localization and mapping, (SLAM) and 2D laser scanners are used. Figure 7 shows an example of the graphical presentation. As the robot is moving in the vessel, a 3D point cloud of the vessel is being created. The position and movements of the robot itself are also shown.

![Fig. 7. 3D point cloud presentation of vessel with FAST.](image)

The FAST can carry an inspection camera, the Gocator, an eddy current array probe and a phased array ultrasonic probe.
Inspection tools

To achieve good quality inspection results that match those performed by a human, standard inspection tools have been used. These have been adapted to suit the deployment method.

Visual Inspection Camera

The inspection camera is the principal tool used to identify possible defects. The primary criteria for camera selection were optical performance and weight. For both the snake-arm robot and FAST robot the Sony FCB-EV7500 was selected. This high performance color camera incorporates a CMOS sensor, 30x optical zoom and delivers full HD at 60fps. The camera blocks are mounted in housings developed by Dekra that also incorporate LED lights. As there is a large range in required standoff between the camera and the inspection target, different LED lenses have been employed to create a specific spreading of the light. Figure 8 shows the cameras for SNAKE, left and FAST, right.

Figure 8. Inspection camera for SNAKE (left) and FAST (right).

Figure 9 shows two images from the inspection camera. The left image shows a weld, partly peeled off coating to the left of the weld and pittings. The right image shows loose debris.

Figure 9. Images from the inspection camera.

Structured white light

Once a possible defect has been identified with the inspection camera, this has to be quantified. To do this a tool based on structured white light, the LMI Gocator 3100 [6], is used. The Gocator is shown in Fig. 10, left image.
The measurement principle is shown in figure 10, right image. The light module emits blue light from an LED in specific patterns. The two cameras are used to create stereoscopic images. The supplied software can be used to measure sizes and depths of pits, for example. The resolution in depth direction is approximately ±0.1mm. Figure 11 shows a result from the Gocator, from a measurement on a calibration plate. The two holes inside the red markings have a depth of 1mm (upper left hole) and 0.5mm (lower right hole. The red markings are made with paint, so what is actually seen is the thickness of the paint layer.

Ultrasonic Inspection

Ultrasonics is used to measure wall thickness on the non-accessible surface of the object. For PETROBOT array technology, an Olympus Omniscan with a 2.5MHz array probe, is used. Dedicated probe fixtures have been developed by Dekra for FAST and SNAKE, the fixture for SNAKE is shown in figure 12, left image. A typical result from a calibration block with flat bottom holes is shown in figure 12, right image. The results are presented as a Time-of-Flight image (top) and a B-scan (bottom).
Eddy Current Inspection

Eddy current inspections are used for crack detection and corrosion measurements. Innospection have developed dedicated probes and fixtures for each of the robots. Caused by the different payloads and operational aspects the designs differed. The different sensors are shown in figure 13.

![Fig. 13. Eddy current probes for SNAKE (left), BIKE (middle) and FAST (right).](image)

The SNAKE fixture consists of a single probe that is scanned over an area using a pendulum movement. The BIKE fixture consists of a double probe. This, however, performs a linear scan transverse to the movement of the BIKE. The FAST fixture consists of a linear array of 8 probes. A result from a scan of a test plate with a crack-like defect at a weld made with the BIKE is shown in figure 14.

![Fig. 14. Result from eddy current inspection of a test plate, using BIKE.](image)

Inspection of pressure vessel

As a test of the applicability of robotic inspection one pressure vessel has been partially inspected using the FAST robot. One important difference between traditional, human, inspections and robotic inspections is that the navigation of the robot needs to be carefully planned prior to the inspection, as a human is better at improvising than robots. For preparation of a scan plan a simulation tool, developed by Quasset, was used. First the vessel as well as the robot were modelled, then different scan- and inspection patterns were tested. Figure 15 shows an image of the vessel with the robot. In the simulation the bright area next to the hole represents the area that is inspected with the camera at this particular instant. For this case, the inspection was focused on the lower half of the vessel. Of primary interest was to detect pitting corrosion.
The resulting scan- and inspection plan were documented in a procedure. During the inspection, the procedure provided valuable guidance for the inspection team. The inspection was performed as a visual inspection, where areas noted to show degradation or indications/defects should be quantified using the Gocator. Figure 16 shows an image from the visual camera and a Gocator measurement from the same area. Encircled in the images is a corrosion pit 12x10 mm, measured to be 0.7 mm deep.

Conclusions

In this paper the progress of the EU funded project PETROBOT for robotised inspection of pressure vessels has been presented. Three different, complementary, robots have been developed. As discussed, the three systems enable robotised inspection capabilities in a variety of pressure vessel designs using multiple inspection tools consisting of cameras for visual inspection, structured white light for profilometry, ultrasonic transducers for wall thickness measurement and eddy current transducers for crack detection and corrosion detection.

The PETROBOT project has conduct a range of integration and laboratory tests of the robots and inspection equipment and is currently being finalised for deployment in real installations of the participating end users.

The PETROBOT project has brought together inspection methods and robotic technology to reduce risks and cost involved in inspection of pressure vessels. PETROBOT comprises the complete value chain, from robot and inspection technology providers, to inspection service providers and end-users. The project has developed robotic deployment platforms and adapted industry standard inspection techniques to demonstrate the benefits of remote pressure vessel inspection.
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