ULTRASONIC AND IRRADIATION PIPE ROBOTS FOR INTERNAL CORROSION MAPPING AND WELD INSPECTION - CASE STUDIES FROM PRACTICE

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ABSTRACT

Inspector Systems is a specialist in manufacturing of tethered self-propelled pipe robots for internal inspection, non-destructive testing and machining of complex pipe systems in the nuclear industry. Due to its flexible modular design the pipe robots are able to get inserted through poor access points (e.g. valves) and to pass in bi-directional travelling vertical sections and numerous bends with small arc radius. The presentation describes the system concept and performance of the pipe robot technology. A modular construction allows the adaption of different operational elements for the respective application. Main focus of the presentation is a) the procedure and practical application of ultrasonic modules for interior corrosion mapping and weld inspection as well as detections of anomalies and b) the functionality and practical application of an irradiation robot (gamma from inside with an isotope) for weld shots. Ultrasonic robot: A gimbal / spring mounted probe holder with UT-sensors moves out and gets pressed against the inner pipe surface, while a centering mechanism keeps the UT-module in the center. Through a continuously rotating of the probe holder along the pipe circumference and a simultaneous forward travelling of the robot, a 100% pipe scanning can be performed as well as internal weld inspections. Due to an own water supply system for ultrasonic sensor coupling, it is not necessary to fill the pipe with a coupling medium. Defects are visible in real time, for later documentation and further consideration the whole inspection is recorded on laptop. The UT-analysis software with A-signal, B- and D-cut channel as well as a color-scaled C-Scan describes the pipe condition. An integrated laser positioned in the 360° rotatable head of the robot in conjunction with a pan & tilt color front camera provides additional the possibility of visual inspections, profile views and laser-sizing of defects. Irradiation robot: The adaption of an external radiographic exposure device for the use of activity sources makes radiography applications from inside of complex pipeline structures possible. Due to an inside positioning the complete pipeline circumference can be tested in one shot within the density range of the isotope. Case studies from projects in nuclear power plants complements the presentation.

1. INTRODUCTION

Technical installations that are subject to stringent requirements should always be kept on the best possible level of operational safety. This applies particularly to installations with their innumerable piping systems that require a high degree of reliability, comfort and safeness. Keeping individual pipeline sections in perfect condition is a crucial prerequisite for the trouble-free operation of the entire system. The pipeline systems therefore have to undergo strict and regular tests of various types which ensures that any damage to the pipes as a result of wear, corrosion, erosion and cracking etc. is detected, respectively prevented at an early stage. Subsequently it can occur that a detected damage is not accessible from the outside and a repair by appropriate means must take place from the inside. All this requires bendable and flexible pipe robots with the possibility to equip with modules for the respective application to carry out the maintenance- and inspection work inside of pipe systems.

Figure 1 - Robot with drive units connected via folding bellows and video/laser-inspection head
2. **SYSTEM CONCEPT**

Main Components:

- drive units (anodized aluminum) with its special rubber coated wheels
- flexible folding bellows (stainless steel)
- inspection-/ testing- or machining module
- electrical housings
- abrasion proofed special cable
- control system (operating unit, monitor, HDD-recorder etc.)

The basic structure of the self-propelled and remote-controlled pipe robots consists of several drive units with its special rubber coated friction rollers as well as inspection-, non-destructive testing- or machining modules who are flexible connected to each other via folding bellows. By means of an adjustable initial tension, the friction rollers made of a special rubber mixture free of chloride- gets pneumatically pressed against the inner pipe wall and are stabilizing and centralizing the robot inside the pipe. As a result, the robot can travel through complex and non-piggable pipeline structures, meanwhile a special cable connection to the control system outside the pipe system provides the energy supply, data transmission as well as the control to the adapted inspection-/ machining modules. In addition the cable connection ensures a safety pull back functionality.

![Figure 2 - Drive unit retracted](image1)

![Figure 4 - Drive unit extended](image2)

![Figure 4 - Special cable with robust plug](image3)

![Figure 5 - Control system e.g. ultrasonic](image4)
The robots are defined according to the following pipe diameter breakdown as standard, specific to the application and on request, different dimensions and customizations are possible.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>MM</th>
<th>INCH</th>
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<tbody>
<tr>
<td>1.000</td>
<td>75</td>
<td>110</td>
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<td>2.000</td>
<td>100</td>
<td>140</td>
</tr>
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<td>3.000</td>
<td>130</td>
<td>200</td>
</tr>
<tr>
<td>4.000</td>
<td>190</td>
<td>325</td>
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<tr>
<td>5.000</td>
<td>310</td>
<td>510</td>
</tr>
<tr>
<td>6.000</td>
<td>440</td>
<td>800</td>
</tr>
<tr>
<td>7.000</td>
<td>750</td>
<td>1.200</td>
</tr>
</tbody>
</table>

Figure 6 - Standard dimensions – diameter range robots

3. SYSTEM PERFORMANCE

The following performance features are given:

- Self-propelled
  - no external drive medium needed,
  - stop at any time

- High degree of bendability and flexibility
  - insertion through poor access points (dismantled valves, flanges etc.)
  - crossing numerous bends ≥ 1.5D
  - crossing welded seams, T-branches and diameter reductions

- Bi-directional travel
  - access only from one side necessary

- Horizontal and vertical travel
  - vertical inclined uphill (up to 90°) and downhill directions

- Online results / monitoring
  - live survey

- Long travel distance (more than 500 m possible)

Figure 7 - Insertion pipe robots into pipe system
Depending on the requested application, the robots can be equipped with different modules for inspection-, non-destructive testing or internal machining like grinding etc. The following describes a selection of two non-destructive testing variation used in different business sectors as well as either in the nuclear industry.

4. ULTRASONIC ROBOT FOR INTERNAL CORROSION MAPPING AND WALL THICKNESS MEASUREMENTS

4.1. Ultrasonic module

A continuously rotating ultrasonic module incl. sensors, mounted between two drive units with flexible bellows connection, is the main component of the ultrasonic inspection robot in order to achieve a complete wall thickness measurement with differentiation between inner and outer defects of the surface while travelling through the pipe.

Centered by a high accuracy pneumatically centering mechanism, the ultrasonic module includes a fixed part and a continuous rotating body.

Figure 8 - Ultrasonic robot

Figure 9 - Ultrasonic module

Centering mechanism with retracted centering arms (three on each side) and green centering wheels.
Rotating part:
The rotating part of the module contains a rotating cylinder and a retainer with water chamber and probe holder for the ultrasonic sensors. The retainer itself is mounted on a pivoting arm. During the mapping process the pivoting arm moves out by using a DC motor and presses the retainer against the inner pipe surface. Due to a gimbal suspension system of the retainer an orthogonally impact to the inner pipe surface (90°) is provided for best possible measurement results especially in terms of pipe ovality, bends, etc.. To provide the echo couple medium a special feature is an independent continuous water supply to the ultrasonic sensor, i.e. it is not needed to fill the pipe with a liquid medium during inspection.

Fixed part:
The fixed part of the ultrasonic inspection head contains different DC motors to execute the rotation of the rotating part and a slip ring who is necessary to transmit the ultrasonic signals as well as water and air supply in order to guarantee a continuous revolving of the contacting probe holder. A fixed zero sensor indicates a signal after each 360° turn meanwhile a circumference encoder system identifies the relative position of the ultrasonic sensors.

Centering mechanism:
The purpose of the centering mechanism is to keep the ultrasonic module always in the center of the pipe while travelling through, independent from different pipe diameters, ovality etc. On the other side this centering mechanism must be flexible enough to cross bends as well as pipe welds or flanges. In total there are two centering mechanisms, in between there is the rotating part located. Each centering mechanism consists of three different pneumatically strokes which are mechanically connected among each other. This design allows a flexible and high accurate centering function.

4.2. Cameras and point laser

The inspection robot is equipped with three CCD colour cameras, each performing in high picture resolution and contenting a LED light source for excellent illumination.

Figure 10 - Rotatable head with front view camera (pan&tilt) and point laser

Figure 11 - Pipe ovality-profile with wrinkle at 270°

Front view camera and point laser:
Attached to the first drive unit the camera and the point laser are integrated into a 360° rotatable head, i.e. the camera is necessary to navigate through the pipe system and can additional also be used for visual inspections (>460TVL, 10x optical zoom, automatic and manual focusing). Because of an additional pan and tilt functionality, every point of the internal pipe surface can be inspected in detail. With the help of the point laser it is possible to verify anomalies like cracks, holes or pitted corrosion areas. At any point on the inner circumference of the pipe spot-measurements can be done with an accuracy of 0.2 mm,
also when the surface is intense shiny, wet or uneven. By the laser, it is also capable to prove/check inner pipe profile/ovality (2D plot). All values (turn- and tilt angle, laser, etc.) are displayed on the laptop and illustrated by means of a title generator on the monitor, these values are then stored along with the camera image and comments on HDD / DVD.

**Sensor camera:**
The sensor camera has a direct view to the ultrasonic sensors to check that the probes are in contact with the pipe surface during inspection and to see the water coupling.

**Back view camera:**
Attached to the last drive unit, this camera is helpful during driving backwards. Two camera pictures can be displayed in parallel (for example front view camera and sensor camera) and recorded on hard disk DVD- recorder in parallel with all other values like drive distance measurement, etc.

### 4.3 Control station with ultrasonic analysing unit

The robot control station controls all functions of the ultrasonic inspection robot and displays all data and operational faults that are necessary for robot driving as well as rotating head control. The ultrasonic analysing unit consists of a powerful laptop including customized ultrasonic inspection software for A, B and C-Scan analysing of up to 8 UT- sensors in parallel and a UT hardware mounted into the robot.

![UT-analyzing software with A- Signal, B- Cut channel as well as colour scaled C- Scan (Time to Flight-Picture)](image)

**Figure 12** - UT-analyzing software with A- Signal, B- and D-Cut channel as well as colour scaled C-Scan (Time to Flight-Picture)

### 4.4 Example Application

The ultrasonic inspection robot is often used in pipeline systems with difficult external access or complex structures for all kind of industrial sectors, at which in nuclear power plants the most common task is to determine the wall thicknesses in different contaminated pipe systems.

An example was an operation at customers premise with following task (Figure 14+15):

- Determination of wall thickness in two bends of a contaminated pipe system
- Determination of surface cracks in longitudinal welds
- ID 220 mm
- Arc Radii 1.5 D
- Insertion through open valve
- Vertical travel
Another further example for inspection in nuclear power plant was the following (Figure 13):

- Integrity measurement of an internal thermosleeve weld
- Determination of wall thickness before and behind the thermosleeve weld
- ID 220 mm
- Arc Radii 1.5 D
- Insertion 90° through open valve

4.5. Example analysis UT- wall thickness measurement

The following example shows an analysis of a typical ultrasonic wall thickness measurement.

**Pipe Data:**
- Material: Steel
- Inner diameter: 311.7 mm
- Outer diameter: 325.9 mm
- Length: approx. 12 m
- Speed of sound: 5980 m/s (Longitudinal wave)
- Wall thickness: 7.1 mm

**Inspection Data:**
- Speed (Rotation): 415°/s
- Speed (Drive): 8 mm/s
- Resolution axial: 6 mm/Pixel
- Resolution radial: 1°/Pixel
Analysis Data:

![Marked Area](image)

**Figure 16 - UT-inspection analysis**

<table>
<thead>
<tr>
<th>Channel:</th>
<th>combined</th>
</tr>
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<tbody>
<tr>
<td>Scan type:</td>
<td>Time Of Flight C</td>
</tr>
<tr>
<td>Cutoff area:</td>
<td>(X: 734.259 mm; D: 857.374 mm) - (X: 752.657 mm; D: 887.839 mm)</td>
</tr>
<tr>
<td>Area Length:</td>
<td>18.398 mm</td>
</tr>
<tr>
<td>Area Width:</td>
<td>30.465 mm</td>
</tr>
<tr>
<td>Minimum:</td>
<td>3.478 mm at (X: 745.967 mm; D: 866.078 mm)</td>
</tr>
<tr>
<td>Notes:</td>
<td>External defect</td>
</tr>
</tbody>
</table>

Result:

The marked area above shows an external defect with the dimension of approx. 18.4 mm x 30.5 mm at 323° and a distance of approx. 7.3 m from the entrance point of the robot. Minimum wall thickness of the marked area is 3.478 mm

5. **IRRADIATION ROBOT FOR INTERNAL WELD INSPECTION**

5.1. **Single-wall radiographic examination technique**

Film-based radiography is an effective NDT technique for locating and evaluating discontinuities that can adversely affect the integrity of an operating piping system. Characteristic discontinuities in welds are incomplete root penetration, burn-through in the root, root undercut etc. Open cracks can be detected, but tighter cracks, even though favorably oriented are detectable only by optimum practice, some cracks might not be revealed at all. The irradiation robot carries out radiographic exposures on pipeline welds in single-wall technique from the center inside the pipe, instead of double-wall technique from the outside.

**Figure 17 -**
Schematic radiographic exposure in single wall technique on girth weld
5.2. External gamma irradiation system

For the radiographic exposures an irradiation rod with a source guide tube of an external gamma irradiation system is adapted to the robot, whereas the radiation source, a low energy isotope (mainly Iridium-192), is housed in a source projector. By a hand crank, the low energy isotope gets propelled from the source projector through the source guide tube to the peak of the irradiation rod (exposure position) and back.

5.3. Irradiation unit

The irradiation robot contents a drive unit and a driven irradiation module who is prepared to take up the irradiation rod of the external irradiation system. Once pneumatically adapted by an arresting system, the irradiation rod is axial mounted at the front of the irradiation unit and will be centered and stabilized by the 1st centering element during the gamma-ray examination. While a fixed colour front camera incl. illumination ensures the robot navigation, two additional axial extendable colour cameras takes care for the correct positioning of the irradiation rod to the weld. The 2nd centering and adjustment element is a pre-angulation system with pneumatic-mechanical clamps for the correct alignment of the irradiation rod in bends respectively in the opposite way to the intrados to insure a correct homogeneity to film density. In case of an emergency the irradiation rod can be released and separately pulled back. A special cable connection to the control system outside the pipe system is used for energy supply, robot control and camera control of the irradiation robot.
5.4. Example Application

The main purpose of the irradiation robot is the radiographic exposures on welds in pipeline systems of nuclear power plants. To distinguish is here between

a.) power plants in operation where after years fatigue reasons can it makes necessary to prove the integrity of welds or after replacement of a pipe or a bend, the new welds must be proved by radiographic testing technology

b.) power plants under construction where the inside radiography gives an extremely advantage in the course of economy

The following is an example for a nuclear power plant in operation:

- Exchange of two bends of a TH-Pipe System
- ID 220 mm
- Wall thickness 24 mm

During a revision two bends was cut out, exchanged and new ones welded. Because of the time consuming process for radiographic testing from outside, the operator of the plant decided to do the radiographic testing for the welds from inside. After insertion through a corner shut-off valve with back flow preventer, the robot was fixed by its centering system to keep the position tight during the examination. After successful exposure the robot was removed through the insertion access point.

Another example is the radiography at a nuclear power plant who is actual under construction:

- Pipe joints of a pipe system
- ID 508 mm
- Wall thickness 38 mm

Radiographic testing is only practiced during the night once a week, that’s because to minimize the risk of radiography injury. In total the preparation time incl. film mounting, radiographic shoot etc. can take almost the whole night. If using the double-wall technique, in total approx. 5 films are needed to radiography the whole weld and that means at least 5 nights for one weld. When considering that only one shoot per week is possible, that means an extremely loss of time for radiography. With the help of the irradiation robot and the single-wall technique, i.e. due to radiography from inside and a film wrapped around the pipe circumference, the process for the inspection of one weld is sped up to 5 times.