A roadmap of SPRINT Robotics

Report nr 16012 rev 1.1
# Glossary

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>AST</td>
<td>Aboveground Storage Tank</td>
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<tr>
<td>BRL</td>
<td>Business Readiness Level</td>
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<td>COT</td>
<td>Cargo Oil Tanks</td>
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<tr>
<td>CS</td>
<td>Carbon Steel</td>
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<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
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<td>DP</td>
<td>Dye Penetrant</td>
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<tr>
<td>FPSO</td>
<td>Floating Production, Storage and Offloading facility</td>
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<tr>
<td>FRP</td>
<td>Fibreglass-Reinforced Plastic</td>
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<td>HAZ</td>
<td>Heat Affected Zone</td>
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<td>IL</td>
<td>Impact Level</td>
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<td>MFL</td>
<td>Magnetic Flux Leakage</td>
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<td>MPI</td>
<td>Magnetic Particle Inspection</td>
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<tr>
<td>NII</td>
<td>Non-Intrusive Inspection</td>
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<tr>
<td>PEC</td>
<td>Pulsed Eddy Current</td>
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<tr>
<td>POB</td>
<td>People On Board</td>
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<tr>
<td>POD</td>
<td>Probability Of Detection</td>
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<td>PV</td>
<td>Pressure Vessel</td>
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<td>ROV</td>
<td>Remotely Operated Vehicle</td>
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<td>ROAV</td>
<td>Remotely Operated Aerial Vehicle</td>
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<td>SS</td>
<td>Stainless Steel</td>
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<td>TRL</td>
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<td>Unmanned Aerial System</td>
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Reading Guide

This SPRINT Robotics roadmap document contains three main sections:

- Chapter 0: the roadmap in concise form, for those who want a quick overview of the most important roadmapping statements and results, supplemented with two case studies;
- Chapter 1 – 3: the main roadmap document, containing the general roadmap for the petroleum and (petro)chemical industry;
- Appendices A – D: four detailed roadmaps, each of which focuses on one of the high priority application areas, as decided by the SPRINT Robotics Program Committee.

Each of these main sections can be read separately from the other main sections and each of the appendices can be read separately from the other appendices.
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3 SPRINT Roadmap

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0 Roadmap in concise form

This chapter presents the SPRINT Robotics roadmap for robotic inspection and maintenance in a concise form. The complete presentation can be found in the next chapters and the appendices. The following sections give a concise overview of end users’ drivers, cost determining factors, relevant developments in robotics and autonomous systems, opportunities for robotics in inspection and maintenance and about testing, demonstrations and qualification. We end with two case studies.

0.1 Drivers in the petroleum and (petro)chemical industries

The most important end user drivers in the light of this roadmap are:

- Safety improvement: human safety as well as environmental safety;
- Cost avoidance and reduction;
- Environmental performance improvement: reduce production of (toxic) waste, avoid leakage and catastrophic events.

0.2 Cost determining factors

If inspection or maintenance cause downtime of equipment, the loss of revenue due to the reduced production rates may quickly become a dominant factor in the total costs associated with inspection and maintenance.

In many applications, much of the off-line time is caused by preparation for inspection:

- Preparation (predominantly cleaning and isolation) for human entry of confined spaces, such as tanks and pressure vessels;
- Scaffolding;
- Removal and renewal of insulation.

Other cost-intensive aspects are transport of a crew to a remote (offshore) site and the number of People On Board (POB) of an offshore installation.

0.3 Developments in robotics and autonomous systems

An important recent development in robotics is the recognition of the fact that in practical applications, robots must be able to work in the real world, as opposed to the ideal, clean and organised laboratory environment. Robots must be able to use the existing infrastructure, such as narrow manways, steep staircases, cage ladders, dirty and slippery surfaces and doors and must be able to handle the presence of unexpected obstacles. The weather may be inclement, equipment must be explosion proof (for example ATEX or IECEx).

Challenges are being organised to test newly developed robots for real-world applications. DARPA has organised a number of robotic challenges in which robots had to perform practical tasks, such as
opening a door, opening a valve and grabbing a tool. Total has organised the Argos challenges (ending in 2017), specifically targeted at Oil & Gas industry application.

A second important recent, and on-going, development is that of autonomy. In the context of this roadmap the following aspects of autonomy seem relevant:

- Systems are becoming, and have become, capable of autonomously executing tasks ranging from simple, basic tasks (for example simple scanning a sensor over a surface) up to fully autonomous navigation and problem solving;
- Autonomously moving robots can be capable of safely sharing the work space with people and even interact with them;
- Autonomous robots can be capable of learning from their (and others’) experience.

The level of autonomy must be carefully selected for the application.

0.4 Opportunities for robotics in inspection and maintenance

The best opportunities for robotics in inspection and maintenance can be found where:

- Use of robots significantly reduces or avoids downtime of the assets, as system downtime is by far the most dominant factor in costs associated with inspection;
- Human entry of confined spaces can be avoided through use of robots. Human entry of confined spaces for inspection is responsible for up to 80% of asset downtime due to preparation requirements. Furthermore it is considered a hazardous activity;
- Robots can replace human operators on remote and offshore sites, as with permanently having a crew on such sites or flying one in (helicopter) high costs are involved;
- Robots can take over hazardous tasks, such as fire fighting and working at height;
- Robots can execute tasks at height or other difficult to reach locations, as the required preparations, such as scaffolding and/or removal/replacement of insulation, are time-consuming and expensive, and may be associated with health risk;
- Use of robots enables significantly more frequent inspection. This may enable close monitoring of progress of a defect, such as crack growth. Knowing accurately the size or severity of a defect makes it possible to keep the asset online longer without compromising safety. The likelihood of unplanned maintenance and catastrophic events decreases as a consequence.
0.5 Testing, demonstration, validation and commercialisation

For the grow from a first lab model to a fully deployable commercial robot and services, a number of steps are crucial:

- The solution must be tested in realistic environments from an early stage on. This requires permanent testing facilities, enabling controlled and repeated testing in realistic circumstances;
- Solutions must be validated/qualified before (commercial) use in live plants;
- Demonstrations must be given under realistic circumstances to show users (service providers) and end users (asset owners/operators) the potential of the new technology;
- Users and end users must use the new technology as soon as it is available, even if it is not yet in its ultimate state. This is needed to gain valuable experience.

Examples of such tests and demonstrations include those held at TEEX\(^1\) and Haugesund\(^2\).

0.6 Case study: Aboveground Storage Tanks

Currently, Aboveground Storage Tanks (AST) must be emptied, taken offline and cleaned for inspection. The long downtime associated with this causes high costs due to lost revenue. Often the most critical part of these tanks is the floor\(^3\). As about 80% of the inspected tanks can be taken back into service without repair\(^4\), avoiding the need to take a tank offline for inspection would have great impact. This could be achieved by using online robotic floor inspection.

Certain technical challenges have been solved already: explosion proof crawlers and cameras are available. Entry of equipment into a full tank, orientation and navigation have been demonstrated in commercial services, be it that the latter were not accurate enough for scanning yet. Integration with NDE methods for high-coverage wall thickness measurement would be needed.

First applications could be in clean tanks with as few appurtenances as possible, and with clear content, so that the camera images would aid in localisation and navigation.

The ability of prior online robotic cleaning would increase the number of qualifying tanks significantly. For such a robot, the basic techniques are ready, too. The business impact would be high.

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\(^1\) TEEX, College Station, Texas; The tests and demonstrations were organised by Chevron and comprised crawler inspection and 360° camera inspection in diverse asset types.

\(^2\) Haugesund, Norway. The tests were organised by Gassco and comprised 360° camera inspection in diverse asset types.

\(^3\) The wall can be inspected from the outside, so usually does not require the tank to be taken offline.

\(^4\) Often repairs are done nonetheless, in order to reduce the risk of later unplanned repairs, while the tank is open anyway.
0.7 Case study: Remote Operator

There are three types of remote robotic operator envisioned:

- **Regular operation.** The purpose of this robot would be to remove human operators from remote (offshore) sites and to take over repetitive activities. The most basic version would be able to move around through the site, see, listen, smell (gas), read dials, decide if anything has changed or readings are outside the allowed range, and report back and raise a warning or alarm when appropriate. A later version would add to this taking samples, pressing buttons and operating valves. Preferably the Regular Operator is fully autonomous, but in many situations a lower level of autonomy would be of great value, too;

- **First responder.** The task of the First Responder would be to react on events. Required functionality would be similar to that of the regular operator (the extended version), with possibly added infrared camera, radiation detector and wind sensors. The first responder would ideally be semi-autonomous. A human operator must always be in control;

- **Emergency response,** for instance fire fighting and rescuing people. The ideal level of autonomy would be low, as this type of role would likely encompass a large degree of improvisation.

The remote operator would need to be able to safely share the working space with human personnel. It would make use of the existing infrastructure.
1 Introduction

This chapter gives the context of the SPRINT robotics roadmap and gives guidance for its use.

1.1 Why a SPRINT Robotics Collaborative?

The SPRINT Robotics Collaborative is an industry driven initiative that promotes the development, the availability and the application of robotics techniques in technical inspections, maintenance and operation of capital intensive infrastructure. The use of Robotics can improve the efficiency, quality and safety of operation, maintenance, inspection and cleaning.

Historically, development of robotics for these applications has been steered by technology push. This sometimes resulted in unpractical solutions for minor problems, while other, major opportunities for improvement remained overlooked. The major aim of the SPRINT Robotics Collaborative is to transform this model into a customer pull model, where the asset owners, i.e. the problem owners who are also the end beneficiaries, define the priorities and the entire value chain defines the path. Knowledge transfer and concerted action play important roles in this process.

1.2 Why a SPRINT Robotics Roadmap?

In short, the SPRINT Robotics Roadmap sets dots on the horizon and sketches the road to these dots. It serves to:

- Identify technology improvements that will progress the use of the technology;
- Translate the technology improvements to common goals;
- Align the industry on goals and priorities;
- Share knowledge and insight with contributing parties from the entire value chain;
- Enable innovators, technologists and researchers to effectively and structurally contribute to the solution of problems relevant to the (petroleum and (petro)chemical) industry;
- Assist end users (asset owners) to adapt their (operational) procedures for the uptake of such new technologies;
- Inform policy makers about the changing landscape, to which they can respond.
In the SPRINT Robotics Roadmap input from the entire value chain is brought together:

- The asset owners, who are the problem owners and end beneficiaries of the technology, define the priorities of the problems to be solved. Since this group in the SPRINT Robotics Collaborative is active in various areas of the petroleum and (petro)chemical industry, their input is seen as representative for this industry;

- The developers of robotics and inspection techniques as well as the system integrators. These parties bring in their knowledge of the current state of the art of supporting technologies, like robot mobility, navigation and autonomy, but also inspection technology and cleaning;

- The service providers. These contribute their knowledge of and experience with inspection and maintenance practice and introduction of new technology and procedures into often harsh environments.

### 1.3 Who should read this roadmap?

This roadmap is relevant for the entire value chain that is involved in inspection and maintenance in the petroleum and (petro)chemical industry, as depicted in section 2.3. Furthermore subsidy providers and policy makers can use the roadmap as a reference.

### 1.4 How should/could this roadmap be used?

This roadmap can (and should) be used by:

- Knowledge institutes, to identify potential use of their developed knowledge and to identify high-potential areas for new or extended research;

- Robot developers, to identify potential use of their developed robots and to identify high-potential areas for new or extended robot development;

- Inspection equipment suppliers, to identify novel uses of their existing equipment and to identify high-potential new developments;

- System integrators, to identify new uses of their existing equipment and to identify high-potential new developments;

- Service providers, to identify new high-potential services or implementations thereof;

- End users, to seek mutual alignment of their mid and long term goals, their priorities and the paths leading to the goals;

- All parties in the value chain, to serve as a basis for providing input and insight, e.g. via the SPRINT Robotics platform;

- Policy makers, as a reference for the development and steering of new policies.
2 General background for the SPRINT Roadmap

This chapter will sketch the background against which roadmapping decisions are made. In the first two sections a very concise characterisation of the petroleum and (petro)chemical industry is given and the main drivers of this industry are listed. The next section presents the value chain involved in inspection and maintenance in the petroleum and (petro)chemical industry. This is followed by a section about high-priority topics and finally the methodology of the roadmap is presented.

2.1 Some characteristics of the petroleum and (petro)chemical industry

Costs

The petroleum and (petro)chemical industry is a capital-intensive industry, i.e. great financial investments are needed in order to make production possible. This holds for the initial building costs, as well as for the costs of inspection and maintenance. As a result costs per production hour are very high. Examples in the context of inspection and maintenance include:

- Premature replacement of risers because they are difficult or impossible to inspect. A riser is very expensive, has a long lead time and loss of revenue due to a riser being out of service is extremely expensive. Costs (direct and indirect) due to an unplanned riser replacement are even much higher;
- Installing and removing of scaffolding to enable inspectors and maintenance personnel to reach the location for inspection and/or maintenance;
- Removing and re-installing insulation for inspection and maintenance of tanks, pressure vessels and piping;
- The requirement to isolate, empty and clean storage tanks and vessels before maintenance and inspection personnel may enter. During this time production is often discontinued.

If inspection or maintenance cause downtime of equipment, the loss of revenue due to the reduced production rates may quickly become a dominant factor in the total costs associated with inspection and maintenance.

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1 Isolation of equipment means to disconnect the equipment from the remainder of the installation, so that unintended inflow of product is impossible
2 As production usually is maximised, there are rarely spare production lines and much of the equipment is on the critical path
Environment
Production in the petroleum and (petro)chemical industry has an important impact on the environment. It has this impact as a direct result of the production processes, as well as indirectly as a by-product of equipment inspection and maintenance. Examples of the latter include:

- Waste production as a result of cleaning of storage tanks, pressure vessels and piping for inspection and maintenance;
- Removal of debris from storage tanks and heat exchangers;
- Increased hydrocarbon flaring to the atmosphere.

Safety
The petroleum and (petro)chemical industry is a potentially hazardous environment. Examples of potentially hazardous activities include:

- Human entry of confined spaces, such as pressure vessels and storage tanks. Confined spaces can be dangerous due to the presence of toxic gas or other substances, lack of oxygen, high temperatures, presence of obstacles et cetera. Rescue operations from confined spaces are difficult and complex;
- Building and removal of scaffolding;
- Working at height (abseilers, scaffolding);
- Working under harsh conditions (off-shore, remote locations). Remote and offshore locations sometimes lack basic services (food, drinking water, shelter), access may be difficult or impossible in inclement weather.
2.2 Drivers in the petroleum and (petro)chemical industry

The most important common drivers for decision making in the petroleum and (petro)chemical industry are listed in the next sections. Insight in these will help in determining goals and visions for the future.
2.2.1 Improve Safety

Improving the (human) safety record is paramount in the petroleum and (petro)chemical industry. Robotics has the potential to improve human safety in the following ways:

- Avoid human entry into confined spaces. This can be done by e.g. sending a robot in instead of a human inspector. The robot can be for example a crawler, an ROV, an ROAV or a robotic arm;
- Avoid human presence in dangerous locations, like offshore installations, working at height, on hot objects or in hot locations. Examples include:
  - ‘Remote operator’: the operator in the plant/offshore is replaced by one or more robots that are remotely controlled by a human operator;
  - Crawler, ROAV or robot arm that works at the dangerous location;
- Guarantee up-to-date knowledge of the state of the asset to minimise risk of potential leakages, ruptures and other unexpected and disruptive events. The robots are capable of generating full digital pictures or measurement results that are more easily stored and checked with previous inspections in comparison to human inspections.

2.2.2 Improve environmental performance

Improving the environmental performance is important for the petroleum and (petro)chemical industry for a number of reasons, including:

- There are legal limits to the environmental stress caused by industrial processes;
- Ethical reasons (the wish to minimise the environmental footprint);
- Public relations.

Environmental performance can be sub-divided into:

- Environmental safety:
  - avoidance and minimisation of pollution, for instance due to leakage. This includes prevention of leakage and, if leakage occurs, minimising its duration and impact;
  - avoidance of catastrophic events like explosions;
- Minimisation of toxic waste. Toxic waste may be produced as a by-product of the production process, but also as a result of a cleaning operation. The latter could be reduced or avoided altogether by avoiding human entry into confined spaces and making the inspection techniques suitable for dirty environments. The inspection may need to be executed with inspection equipment submerged in the product.
2.2.3 Increase operational efficiency

In the realm of this roadmap the operational efficiency is best increased by decreasing downtime. For many activities such as inspection and maintenance of equipment, the equipment in question must be taken offline. In practice this often means interruption of production. In many cases this loss of production could be reduced dramatically by avoiding the need for the human inspector to enter into the equipment.

2.2.4 Costs: cost avoidance + cost reduction

Costs can be reduced or avoided by reducing or avoiding expensive actions and operations, such as: scaffolding, cleaning, taking the asset offline and human entry into confined spaces. Often the ‘cost’ driver overlaps with other drivers. For instance by developing/using a different inspection method, the cleaning requirements for the surface to be inspected may be reduced. This enables:

- savings on cleaning costs;
- a reduction in the environmental impact due to the reduced amount of toxic waste sent for disposal;
- savings on the costs of processing toxic waste;
- a reduction in overall downtime;
- an improvement in safety, because cleaning personnel need not enter the vessel (confined space) anymore.

2.3 Value chain

The value chain that is active for robotic inspection and maintenance in the petroleum and (petro)chemical industry is shown below.

System integrators develop and build the systems, technology and procedures that are used by industrial service providers to supply their services to the end users. The system integrators build on...
the output of robot developers and inspection equipment developers and suppliers, who, in turn, build on the output of knowledge institutes. It is not uncommon that the roles of system integrator and robot builder are combined in a single party, sometimes also combined with that of inspection equipment building. Regulators and lawmakers set the legal landscape in which inspection and maintenance take place.

Dotted arrows represent knowledge transfer, while solid arrows represent material transfer (goods). Roughly speaking the purple dotted arrows represent part of the work of SPRINT Robotics. This includes this roadmap.

This roadmap is authored to align the inspection and maintenance related activities of all parties in the entire value chain in a way that ultimately and optimally solves the asset owner’s problems and challenges.

2.4 SPRINT roadmap priorities

The SPRINT Robotics Program Committee (PC) has defined the following application areas to have the highest priority for improvement. Therefore this roadmap centres on these areas:

- Storage tanks;
- Pressure vessels;
- Piping;
- Remote operator, with no particular order between these four.

Appendices A to D present the roadmaps for these application areas.

Other high-potential applications selected for the development of business cases include:

- Emergency response – Unmanned Aerial System (UAS);
- FPSO Cargo Oil Tanks inspection;
- Vessel (e.g. FPSO) external hull cleaning and inspection.
2.5 Roadmap methodology

For each application area a number of visions are described at high level. The visions are presented in a bubble graph like this:

![Innovation Landscape Map](image)

The horizontal axis represents the business readiness, defined as the readiness of the supplying business to develop and deliver the solution (method, equipment and service). The business readiness can be expressed and quantified in the Business Readiness Level (BRL), ranging from 1 (idea) to 9 (ready for introduction), see Appendix E.

The vertical axis represents technological maturity, which can be quantified in the Technology Readiness Level (TRL), also ranging from 1 (first idea) to 9 (mature), see Appendix E.

The size of the bubble relates to the business impact of the new solution, expressed as Impact Level (IL), ranging from 1 (little to no impact) to 5 (overwhelming impact), see Appendix E.

The bubble graph is an illustration that requires additional information before conclusions can be drawn. However, it is a means that quickly gives some insight in the potential of the proposed solution. The following serves as an aid for the interpretation of these bubble graphs:

- In the top-right corner are the solutions that are ready for introduction. Solutions in that area need not have very big impact to be profitable;
- The bottom left corner is the area of first ideas and dreams. Usually the costs of development to reach high TRL and BRL are significant. Their (potential) impact should be high to make them worth pursuing;
- Ideally development from low TRL and BRL is along the diagonal: as technological maturity grows, the business organisation is adapted to the level required for the next steps. This process continues until the technology is of such a level that it is capable of solving the end user's problem and the delivering organisation is ready to produce the equipment and deliver the services;

- A low TRL and/or BRL is not per se equivalent with high required investment of time and/or money. This information is not present in the graph.
3 SPRINT Roadmap

This chapter will sketch a general roadmap for robotic inspection and maintenance in the petroleum and (petro)chemical industry. It starts with describing the customer value proposition in this context, followed by a section about opportunities for robotics. Sections 3.3 and 3.4 give an overview of the current technological landscape and the existing and required developments. Finally section 3.5 proposes a process of adopting robotics.

3.1 Customer value proposition

Technology improvements will provide new solutions for inspection and maintenance challenges in the petroleum and (petro)chemical industry. The customer value propositions will mainly be found in two categories:

- remote or online inspection;
- remote operations and maintenance activities.

These customer value propositions link to major business drivers in the domains of safety, costs and environmental impact. Examples include:

- Online inspection of (atmospheric) Aboveground Storage Tanks;
- Internal inspection of pressure equipment without human entry;
- Remote operation of unmanned sites;
- Inspection of piping systems without scaffolding.

In the domain of SPRINT, the most expensive activities, in terms of safety, costs and/or environmental impact, include [between square brackets the related drivers]:

- (Preparation for) human entry of confined spaces [safety, costs, environment]. Human entry of confined spaces is subject to strict safety measures, including isolation and thorough cleaning of the asset. This is not only costly, but also time consuming, thus often resulting in high loss of revenue. Furthermore the waste produced in the process has an unwanted negative impact on the environment and is costly. Human entry of a confined space is considered a safety risk;
- Scaffolding [safety, costs] is expensive, and building and removing scaffolding is associated with human safety risks;
- Working at height [safety];
- Removing and replacing insulation [costs, safety];
Taking asset offline [costs]. Offline costs of assets are associated with the loss of revenue due to reduced production rates;

Cleaning assets for inspection or maintenance [costs, environment], see above;

Transport crew to remote/unmanned site (offshore, onshore) [costs], often by helicopter or boat;

People On Board (POB) an offshore manned facility [costs, safety].

In general, the value propositions will centre on avoiding or reducing one or more of the above mentioned activities, or avoiding or reducing their adverse effects. For example:

- Waste production may be reduced or avoided, resulting in a lower environmental impact and waste processing costs;
- A different inspection technique may avoid or reduce the need of insulation removal and scaffolding.

### 3.2 Opportunity description

In this section four concrete technical opportunities will be sketched. For a more extensive and complete description, the reader is referred to the appendices A to D. These opportunities, when realised, will impact the business significantly. Although only four in number, they are thought to be representative for the petroleum and (petro)chemical industry as a whole. Finally this section describes the opportunity for autonomy in inspection.

**Online tank inspection and cleaning**

The opportunity created by online inspection of tank components, as opposed to offline inspection, is to avoid entry of the tank for the sole purpose of inspection. This avoids the costs associated with the tank being out of service, the costs of emptying, opening and cleaning of the tank, and furthermore avoids personnel working in a confined space.

Online inspection, if done timely, will also reduce the risk of unplanned maintenance due to unexpected failures, because damage is likely to be detected in an earlier stage. It thus may aid in planning offline inspection (if still needed additionally) and maintenance, and, in case of a backlog, in prioritising assets for inspection and maintenance.

As the tank floor often is considered the most sensitive area of a tank, a useful staircase of development would first focus on online tank floor inspection (corrosion, cracking and settling, in this order), followed by inspection of the roof support structure. Parallel to this, online cleaning would be a valuable opportunity, as this will be needed for inspection of certain tanks containing deposit, but also as a form of maintenance of these tanks.

**Pressure vessel inspection without human entry**

Conventional inspection of a pressure vessel requires a human inspector to enter the vessel. The required preparation for this (such as cleaning and isolation) is time consuming and costly. For most of the preparation activities, the vessel must be taken offline, which directly translates into loss of revenue due to reduced production rates, and thus to high costs. Much of this preparation can be
avoided by using robotic inspection so that the inspector need not enter the vessel. This also increases human safety, as any entry of confined spaces is associated with risk and sometimes (very uncomfortable) protective clothing and even an oxygen mask must be used.

A useful staircase of robotic pressure vessel inspection would start with visual (camera) inspection of the vessel internals (presence, deformations, damage, erosion etc.), the inner surface of the wall for corrosion, the welds and heat affected zone for cracking and the nozzles. A next step could be accurate measuring of internal corrosion (general as well as pitting) and detailed crack detection and measurement, followed by inspection of the cladding layer if present.

**Piping inspection without scaffolding**

The most costly aspect of inspection of ( uninsulated) piping is the building and removal of scaffolding. Furthermore construction and removal of scaffolding is not void of human safety risk. Robotic piping inspection is thought to be able to remove these adverse effects.

For the development of robotic piping inspection several staircases can be developed in parallel. One staircase describes the development of inspection techniques, ranging from visual inspection of the pipe surface, the coating and pipe supports, via measurement of remaining wall thickness for general wall thinning and pitting corrosion up to the detection of cracking. Measurements can be executed for instance by means of local scanning of the piping, such as UT thickness gauging, but also from a distance, such as employing guided waves.

Another staircase describes the (complexity of the) geometries of the asset, ranging from simple, straight pipes more or less free in the air, via pipes close to the ground or near other obstructions, to dense pipe racks, pipe bridges, junctions, valves et cetera.

The possible presence of insulation adds another complicating factor, as the insulation completely covers the pipes. For this situation the same considerations apply as for uninsulated piping. The added opportunity in this case is to execute the inspection without or with only very limited removal of the insulation. Several inspection techniques have potential value in this respect, including PEC, acoustic resonance and guided waves. Also, for the further away future, tiny robots equipped with miniature inspection hardware, crawling underneath the insulation seem feasible.

Depending on the characteristics of the inspection techniques and equipment employed, the carrier may be a drone, a crawler, a cherry picker, a robotic arm, a snake robot or any of the microbots that are currently in early stages of development. Where on uninsulated piping magnetic crawlers and legged robots are a possibility, for insulated piping other means of attraction must be employed, such as suction.

**Remote operator**

Having robots execute operational tasks at an unmanned, remote site avoids the need for an on-site crew, thus avoiding the costs of the facilities and transport and the risks involved with working at remote sites. A logic staircase would start with simple, light tasks such as monitoring the equipment, processes and environment, for instance by reading gauges, taking samples and recording visual information. In a next step the robotic system could determine changes and trends, followed by reacting on events. Parallel to this, a line of robots might be developed for tasks like pressing buttons, operating valves, fire fighting and small, possibly temporary, repairs.
Autonomy
An opportunity that does not focus on a particular application, asset type or action is autonomy. Many potential robotic tasks and actions in the context of inspection, maintenance and operation in the petroleum and (petro)chemical industry can profit from autonomy in various ways:

- Autonomously executed robotic inspections can be repeated much more frequently, resulting for example in more accurate trending and monitoring and a shorter delay between the occurrence of an event and its detection;
- An autonomous inspection robot can inspect continuously, which would strongly relax time constraints, as no (costly) human involvement is required;
- Autonomy makes swarm robotics possible: the execution of a task by many simple, cheap, small, even dispensable, robots, instead of by a single complicated, expensive robot;
- Autonomy can result in increased repeatability of an inspection or measurement;
- A remotely operated robot can be made to autonomously execute selected functions that are difficult or tedious for a human operator, or require high accuracy or repeatability.
3.3 Technology landscape

The current technology landscape for robotic inspection and maintenance in the petroleum and (petro)chemical industry has begun to move towards robotised execution of tasks. Developments of the past years include:

- ATEX compliant crawlers for online tank floor inspection are currently available. Inspection methods implemented include visual and infrared inspection and UT remaining wall thickness gauging. The crawlers are able to cope with limited sludge/deposit. Coverage is improving, but should be increased significantly further;

- Crawlers capable of negotiating the landscape of a processing plant are under development and the first prototypes have been tested. These are capable of taking samples, video recordings and performing simple actions. Further plans for developing a scaled down version that can be smaller and cheaper are in a final decision stage;

- ROAVs (drones) are being used for selected tasks such as flare tip inspection and recording thermographic images;

- FPSO water ballast tanks are being monitored with mini-ROVs. Their primary task is monitoring crack length. By avoiding human entry, the inspection frequency can be every 3 months. With human entry, costs would be prohibitive;

- Arm and snake robots have successfully been used for certain industrial inspections and service tasks recently;

- Microbots, with sizes ranging from insect to mouse, are subject of study at universities. This not only focuses on isolated aspects, such as autonomy or co-operation, but also on concrete applications such as autonomous inspection of the coating of the support structure of bridges;

- Swarm robotics is another example of university development: the co-operation of many cheap (small) robots that on their own have little power, but together are able to execute involving and complex tasks;

- Localisation and navigation are important aspects, for which recent developments have become available for practical applications in product (online applications). Accuracy is an important issue, as this relates directly to (guaranteed) coverage. It is desirable that accuracy improves an order of magnitude for applications such as online tank floor inspection.

So far, robotic inspection operation has always been executed by means of remote control. However, advances in the domain of autonomy in other areas are impressive. This ranges from automated warehouses to self-driving cars and in social contexts such as elder care and health care. Co-operating and co-existing with people is in an advanced stage in certain fields. Autonomy in robotics for the petroleum and (petro)chemical industry is currently in the ‘challenge’ stage.
3.4 Technology Goals

Keeping equipment online
For certain assets, such as storage tanks, keeping the asset online during inspection is of prime importance. Developing inspection and supporting techniques that make full online inspection possible is therefore important. Aspects that need further development include:

- Improving coverage for AST floor inspection;
- Coating inspection for tank floors and walls;
- Inspection of appurtenances and of the roof support structure;
- Accuracy of localisation;
- Online removal of deposit, including the solid, wax-like form.\(^7\)

Avoiding human entry of confined spaces
Other assets will be taken offline for inspection but avoiding human entry of the asset would generate significant gains in the domain of the business drivers. Crawlers (visual and UT), snake robots (visual) and arm robots (visual) have already been developed for the more straightforward applications. More required developments include:

- Crack detection (other than visual);
- Inspection of more complicated appurtenances.

Negotiating the environment
Applications such as ‘remote operator’ and autonomous inspection may require the robot to negotiate the site, using the existing infrastructure. Although moving over a level surface (ground level) is no problem for the average robot, the ability to climb a practical, regular staircase is not yet well spread, and climbing a cage ladder or similar will need to be developed. Surfaces need not be clean or dry.

Visual inspection
Most, if not all, inspection methods lend itself to robotic deployment. However, with the future of online inspection and inspection without human presence, the focus may need to shift away somewhat from visual inspection to other methods:

- Working online means that there may not always be a free view on the surface to be inspected, either because the asset is filled with non-transparent product, or the asset has not been cleaned before the inspection;
- Direct visual inspection of a surface where the line of sight and line of illumination are easily and directly controllable often becomes more difficult if performed with a camera and monitor.

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\(^7\) Online removal of lose deposit is well underway. However, the solid form, which can be present in the petroleum industry as an oil product and in the petrochemical industry after polymerisation, is (even) more difficult.
Hence, traditional visual inspection may need to be replaced by methods such as UT, acoustic resonance, electromagnetic or other techniques. Hardware and procedures will often need adaptation to robotic deployment. Applications would include (internal) corrosion and cracking research.

**Autonomy**

Since autonomy is available in many related applications, it is important now to translate this available experience to inspection robotics for the petroleum and (petro)chemical industry. Besides technical aspects, the following aspects are particularly important:

- Autonomy needs to be fail safe and may never result in rogue robots roaming the site or creating dangerous or unintended situations;
- Autonomous robots must be able to work safely in the presence of human personnel;
- It must be proven for each application that autonomous robots work according to the intentions under all practical circumstances and that the (inspection) results are of sufficient quality and indeed represent the object’s health status;
- The possibility of failing autonomy must be considered and measures limiting the adverse consequences must be defined and implemented. Liability in case of failure and risk or damage must be discussed;
- It is essential for autonomy to select the right level of autonomy. This may range from full remote operation via semi-autonomy to full autonomy. Semi-autonomy will consist of remote operation where certain, well selected, well delineated tasks are executed autonomously, such as moving to a certain location or scanning a specified area.

**Corrosion Under Insulation**

Inspection of insulated piping may require, depending on the chosen solution direction:

- Further development of measuring remaining wall thickness through insulation. This should include very local corrosion such as pitting and the narrow track as produced by acid product components;
- Coating inspection through insulation;
- If robotic inspection requires a crawler, the crawler must adhere to the pipe based on different principles than magnetism;
- Robotising methods for the detection of humidity in the insulation, for example thermographic images or neutron backscatter;
- Further development of an inspection technique for the pipe supports and the sections of the pipe that are covered by the supports.

**Data processing**

Robotised and autonomous inspection are likely going to generate inspection data at a rate and volume that will be less suitable for human processing. Therefore automated processing and archival of the raw data will be required. This processing must include detection and sizing of
important parameters such as remaining wall thickness, defect statistics (severity, location, spatial distribution etc.), but may also require automatic trend calculations, and raising of alarms and warnings.

### 3.5 Managing the process of adopting robotics

For the grow from a first lab model to a fully deployable commercial robot and services, a number of steps are crucial:

- The solution must be tested in realistic environments from an early stage. This requires permanent testing facilities, enabling controlled and repeated testing in realistic circumstances;
- Solutions must be validated/qualified before (commercial) use in live plants;
- Demonstrations must be given under realistic circumstances to show users (service providers) and end users (asset owners/operators) the potential of the new technology;
- Users and end users must use the new technology that is there, even if it is not yet in its ultimate state. This is needed to gain valuable experience, for the developers, for the service providers and for the end users (asset owners/operators);
- It is essential to define a feasible staircase when robotising tasks, without trying to solve all problems from the start. Certain assets are known not to have certain defect types, making inspection less challenging. Certain vessels have only little appurtenances, making moving and navigating inside the vessel easier. Depending on the statistics, such easier cases may well be a sound basis for a business case. See below for an example;
- Where needed, regulators must be involved from an early stage, to fit robotic inspection seamlessly into the legal inspection framework.
In these tanks no significant defects were detected, with the exception of cracking in certain well defined structures and locations. The conventional solutions would have been to either monitor crack growth very frequently or to take the entire FPSO out of service for unplanned maintenance. Both options would have been very expensive. However, the solution that was finally selected was to use a standard mini-ROV equipped with a camera to inspect the cracks every 3 months. This was a quick and relatively very cheap way to keep the FPSO in operation until the next docking was planned. The experience gained this way will be used for further development of FPSO water ballast tank and possibly even for cargo oil tank inspection.

Understanding the current practice and the underlying requirements of the inspections, as well as the potential of (future) robotic solutions are prerequisites to optimally map the current practice to the future practice. Activities and working order may need to be re-arranged in order to suit the opportunities and limitations best.
Appendix A Aboveground Storage Tanks

This Appendix presents the roadmap for inspection and maintenance of Aboveground Storage Tanks (AST). An important role is played by painting the landscape of AST inspection and maintenance, which is the basis for the roadmap.

In the first section a general background of ASTs is given. This is followed by sections about the high-level requirements for AST operation, the functional requirements for inspection and maintenance, and the current inspection and maintenance practice. Section A.4 presents the critical tasks of inspection and maintenance in the light of the asset operator’s drivers. These tasks impact safety, operational efficiency and the environment the most. The next two sections present the actual roadmap: section A.5 presents the visions, while section A.6 gives an overview of the visions in the format of a bubble graph. The last section lists the most important capability gaps between the visions and the current status quo.

A.1 General background of Aboveground Storage Tanks

In an AST product is stored for variable time periods. The entire construction is often built up from steel plates welded together. On the floor these can overlap (lap welded) or be butt welded. The walls (shell) and the roof are butt-welded.

An AST can have a fixed or a floating roof. Both types can have roof supports. In a fixed roof tank these permanently support the roof, whereas in a floating roof tank the roof supports support the roof if it is in its lowest position.

A floating roof tank has a roof drain that needs to move with the roof and therefore has a number of joints (swivels). These joints can leak and thus let oil in, which then finds its way to the environment.

A floating roof can be an external floating roof, where the floating roof is the only roof, or an internal floating roof, where the floating roof is covered by a fixed roof.

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8 © illustrations Virginia Department of Environmental Quality, Virginia, USA; and AGI, Biggar, Saskatchewan, Canada
9 With an exception for certain chemical storage tanks, see section ‘chemical storage tanks’
The below illustration\(^\text{10}\) clearly shows the (external) floating roof construction with its seal, the roof supports (legs) and drain system with the swivels. The legs consist of an outer sleeve, which is fixed, and an inner leg, which can be up (during service) or down (out of service, for support of the roof in its lower position).

Often access is possible through a manhole in the roof\(^\text{11}\) and through a manhole/manway in the side wall, near the bottom. The product can have a range of viscosity values and be clear or have various degrees of deposit. If the product has a high viscosity in the prevailing climate, there can be heating coils mounted above the floor.

\(^{10}\) © Anson Industries, http://www.ansonindustry.com/

\(^{11}\) Since the roof may be in a bad state, it is often not allowed to walk on the roof, unless strong safety measures are taken.
For certain (often aggressive) products, the tank (floor and lower part of the wall) may be coated. Usually this is a coating of several mm thick. The type of coating is tailored to the type of product, particularly to the aggressiveness (acid, caustic).

The product contained in an AST may have a water phase on the bottom (water is lighter than most oil products) and/or an aggressive vapour phase immediately below the roof. This may cause a particularly corrosive environment at those locations.

**Deposit and corrosion scale**

Certain types and qualities of contents may form deposit (sediment), including:

- Aviation grade fuel. The very little deposit that may be present here is generally wiped off and is of no concern in the context of this roadmap document;
- Crude oil. Crude oil usually has deposit. This does not impede the operation of the tank as such (although it can significantly reduce the tank’s usable volume). The only problem may arise in case the product is fed into a refinery. To avoid the crude deposit from entering the refinery system, the deposit is stirred up with a mixing system and then pumped to another tank where it is left to settle. The clear product is then carefully pumped back.
- Chemicals with a tendency to polymerise. The polymer residue can take all kinds of forms, ranging from soft residue to hard blocks of residue. Especially the hard form is tough to remove and clean;
- Corrosion scale is a deposit that is formed as a result of corrosion.

The presence of deposit poses the following problems:

- It reduces the tank’s capacity significantly, as the layer may become several meters thick;
- In floating roof tanks, it may make landing the roof properly impossible;
- It is considered waste, which has to be dealt with in an environmentally responsible way;
- It complicates access to, and thus inspection of, the floor and lower section of the wall and certain appurtenances.

**Inspection**

Inspection of the wall and roof can usually take place from the outside. The floor is generally inspected from the inside. The required inspection coverage is as high as reasonably possible, and includes the welds and zones directly adjacent to the welds (Heat Affected Zones (HAZ)). The floor plates that connect to the wall (annular plates) deserve extra attention, as they are most susceptible to fatigue cracking, due to the changing wind load on the wall and the changing product load on the floor. If a steel floor (and the lower part of the wall) is coated, usually the coating is removed before the inspection is executed and re-applied afterward. The floor and the roof supports are prone to corrosion: general wall thinning as well as pitting.

With the current state of the art, the AST must be emptied, cleaned and de-gassed before human inspectors can enter for the inspection. Depending on the type of product stored in the AST, considerable debris build-up may occur over time. This can take the form of loose, sand-like
material, but also, particularly if build-up is allowed to develop over time, compact into a more or less solid substance.

**Chemical Storage Tanks**

In the (petro)chemical industry, tanks are used to store liquids and dry bulk materials (powders, particles). The vast majority of the storage tanks in the (petro)chemical industry are very similar to those in the petroleum industry. A small amount of the chemical storage tanks (typically 1 – 2%) is made of synthetic construction material. Sometimes the design differs slightly.

Construction materials most often used include:

- Carbon steel, stainless steel (CS, SS);
- Fibreglass-reinforced plastic (FRP);
- Dual laminate, which is a hybrid system made of a specialised thermoplastic liner on the inside and a FRP structure on the outside. The liner can be matched to specific chemical requirements;
- HDPE, PE.

In the chemical industry, CS tanks are often lined completely (not just the lower part) with a coating or liner that is specific to the product contained in the tank. As this liner completely protects the outer layer of the wall, corrosion allowance in CS tanks in the (petro)chemical Industry is less than that in the Petroleum industry. The liner is not removed before inspection, but rather subject of inspection.
A.2 Functional requirements for inspection and maintenance

An operator will have several high-level requirements driving the inspection and maintenance program, including:

- Having up-to-date information on the condition of all components of the tank;
- Managing the cleanliness of the tank. Requirements may vary, depending on the use of the tank and the product contained;
- Minimising cost and downtime related to inspection, cleaning and maintenance;
- Minimising the risk of unplanned maintenance.

Guideline documents such as API RP-575\(^\text{13}\), API-653\(^\text{14}\) and EEMUA-159\(^\text{15}\) on inspection, maintenance, alteration and repair provide guidance for (time-based) inspection intervals for tanks that may operate in various conditions. The guidelines also allow an operator to apply a risk based inspection assessment to plan inspection events.

The guideline documents provide check lists of inspection tasks when the tank is in-service and out of service. The latter group is relevant for online inspection tools.

\(^{12}\) © illustration by Chemstore Group, www.chemstoregroup.com.au

\(^{13}\) API-575: Inspection Practices for Low-Pressure Storage Tanks

\(^{14}\) API standard 653: Tank Inspection, Repair, Alteration, and Reconstruction

\(^{15}\) EEMUA Publication 159 Above ground flat bottomed storage tanks - a guide to inspection, maintenance and repair
ASTs are inspected according to the following high-level functional requirements:

1. Floor plates:
   a. Assessment of the remaining local wall thickness. The required coverage is 100% or as close to that as possible. The defect mechanism is corrosion (general as well as pitting);
   b. The floor ‘settlement’ is determined by measuring the angle between wall and floor. This is a measure for the deviation in geometry of the tank resulting from the changing strain caused by filling and emptying the tank and the changing wind load on the walls;

2. Annular floor plates:
   a. See floor plates, plus:
   b. Assessment of cracking, particularly in/near the weld connecting the wall to the floor;

3. Assessment of cracking in the floor welds and Heat Affected Zones (HAZ);
4. Assessment of corrosion of the roof supports and sleeves (where present);
5. Assessment of corrosion of the roof (shell). Usually this can be done by means of external inspection;
6. Assessment of corrosion of the roof;
7. Floating roof tanks: assessment of the state and fit of the seal;
8. Floating roof tanks: assessment of corrosion of the pontoons;
9. Floating roof tanks: assessment of the swivels of the roof drains and (occasionally) a spot measurement of the wall thickness of the tubes;
10. Assessment of the state of the appurtenances (sumps etc.);

Nrs 6 and 7 can be done from the outside, while the tank remains online. Of the offline assessments, nrs 1 – 3 are the most critical ones. For these a high Probability Of Detection (POD) is required, in line with international standards\(^\text{16}\).

### A.3 Current practice

Currently ASTs are inspected as follows:

1. Floor plates are inspected when the tank is offline (out of service). Methods used include:
   a. Magnetic Flux Leakage (MFL) and Slofec, mainly for screening;
   b. Ultrasonic Testing (UT) for local absolute measurements of remaining wall thickness, at for example five locations per floor plate plus where wall loss is detected;

Electro-magnetic methods, such as MFL and Slofec, cannot properly inspect the Heat Affected Zone (HAZ) near welds, nor the welds themselves. Furthermore inspection equipment imposes geometric limitations. If for example heating coils are mounted low above the floor, inspection equipment (or their sensors) cannot reach the area underneath the coils.

If a tank floor is coated, the coating may be removed after the tank is emptied and cleaned, and re-applied before it is taken back in service. Nowadays many asset owners use adequate...
coatings that have a life expectancy that is considerably longer than the maximum inspection interval. Therefore good quality coatings are replaced after a service life equal to the maximum inspection interval. If good, reliable inspection methods for floor coatings exist that can safely be used in the given context, then the service life of coatings could increase even further. However, the consequences of a failing coating are high, as access of the aggressive product to the bare floor plates might soon develop into a leakage;

2. Annular plates: see floor plates. Additionally the weld connecting the wall to the annular plates and the adjacent zone are 100% inspected for cracking by means of UT. This is related to the potentially high bend loads they may experience;

3. Welds and the HAZs are often inspected by means of vacuum boxing, to find holes (in the form of cracks over the entire plate thickness). The weld connecting the wall to the floor and its HAZ is inspected 100%, visually and by means of UT;

4. Local floor deformation due to settlement is assessed visually and by means of a laser level;

5. Roof supports are inspected visually and with UT spot measurements, typically near the bottom and the top. Guided wave inspection of roof supports is in an experimental stage. Roof support sleeves are inspected visually and if needed the remaining wall thickness is measured by means of UT spot measurements. The top side (protruding upward from the roof) is most prone to corrosion;

6. Wall: can usually be inspected from the outside. If the tank is insulated, the inspection is done from the inside or with for example Pulsed Eddy Current through the insulation (but this is not always possible). The most sensitive area is the top zone, including and above the wind girder(s), so this is inspected most intensively. Whenever possible, inspection is done with a magnetic crawler, in order to avoid scaffolding. However, crawlers have their limitations: they often leave a certain margin on the side unscanned and cannot pass wind girders. If Corrosion Under Insulation is suspected, removal of the insulation is most common;

7. Roof: visually inspected from the outside, also with electro-magnetic methods and UT thickness spot measurements. The frame of the roof is inspected visually, usually from the floor using binoculars. For a floating roof, the seal is routinely replaced before it reaches a service life equal to the maximum inspection interval. The walls of roof pontoons can also be inspected from the outside. A thorough assessment of the roof structures requires internal inspection, though;

8. Roof drains are inspected visually. Swivels are replaced routinely, as they are relatively cheap. Occasionally the tubes are inspected with UT spot measurements (remaining wall thickness);

9. Appurtenances, such as sumps and heating coil supports, are inspected visually and if needed with UT (spot measurements for remaining wall thickness). This always includes the sump, as usually there will be water in the sump, making a corrosive environment.

The majority of these inspections currently require the tank to be taken offline.

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17 Currently 20 years. It is expected that this legal maximum interval will be increased to 25 years
18 Crawler with magnetic wheels, so that it can drive over vertical walls
The above described current practice is the situation in case there is no backlog in inspection and maintenance. However, if there is a backlog, the regime largely depends on the precise nature of the backlog and other circumstances. These aspects fall outside the scope of this document. In case of a backlog, online inspection could play an important role, though.

### A.4 Critical tasks

The tasks in AST operation/inspection/maintenance that are currently on the critical path are identified as follows:

1. Emptying the tank, unless the inspection (and repair if needed) can take place in a tank that contains product;
2. Removal of debris from the floor, unless inspection can take place through the debris and repair is not needed;
3. Repair. If inspection reveals significant damage, the tank needs repair. This can take the form of welding patch plates over corroded plates, replacing entire plates, replacing or reinforcing (roof or heating coil) supports et cetera.

The solutions presented in the next sections all aim at reducing the impact of one or more of the tasks listed above, either by decreasing the time needed to perform such a task, or by removing the execution of the task from the critical path. Some of these solutions follow parallel tracks but there are differences in time frame.

### A.5 Visions

This section presents the visions that were formulated during the SPRINT Programme Committee and Participants workshop in London, September 2016.

#### A.5.1 Offline remote inspection

Offline remote inspection can avoid human entry into the tank for inspection. As a consequence cleaning requirements are much less stringent. The tank can be opened to let a robot, e.g. a crawler, enter the tank. The robot may or may not be tethered. Tethering can be a complication if furniture like heating coils is present, as care must be taken that the tether does not get stuck or entangled. Robots like these are under development and have been demonstrated in a practical context. An inspection executed in this way is very similar to the current practice. Hence both TRL and BRL are estimated to be 6. As the tank does need to be taken offline, the business impact is estimated to be low: level 2.
A.5.2 Offline autonomous inspection

The step from the offline remote inspection mentioned above to offline autonomous inspection is not large. The main value of this option would be:

- To cut down on the number of operators and on operator time;
- To improve inspection quality by (automatically and accurately) linking the inspection data to the position in the tank;
- As an intermediate step towards online autonomous inspection.

This solution is estimated to have a TRL and BRL of 5, whereas the business impact would be 2.

A.5.3 Online remote cleaning

Online remote cleaning is likely going to be a pre-requisite for certain online inspections. Cleaning is not only of value for inspection, but often also for operation of the tank, be it that it strongly depends on the product contained in the tank and how often cleaning is required for tank operation. Mild deposit often does not impede proper operation of the tank.

Cleaning operations and equipment do exist and are used on a routine basis. The TRL for fully remote and online cleaning is still at level 3, but the business readiness is estimated to be 5. Given its significance for online inspection and for tank operation, as well as the number of tanks involved, the business impact of online cleaning would be 4.

A.5.4 Online inspection of clean tank

Online inspection of a tank can generate business impact when a tank satisfies broadly two conditions:

- Online inspection can address all critical inspection tasks needed for a particular tank;
- There is no immediate need for repair (given the absence of online repair tools).

The technical challenge of online inspection tools is high, with inspection requirements as mentioned in section A.2 and operational requirements such as explosion proof equipment, entry of equipment into a full tank, accurate orientation and navigation and working in products at elevated temperature or of a corrosive nature. However, not all of these requirements need to be met to generate a positive business impact:

- In certain tanks certain defect mechanisms are known not to be active or are even impossible, so inspection for that defect type may not be required;
- Sometimes a tank is known to be in good state. This may allow for online inspection with methods or equipment that have a lower POD or sizing capability. Based on the statistics of
the detected defects, it is decided if a more thorough, offline, inspection is required, or that no further inspection is needed for the time being and the tank can remain online\(^\text{19}\);

- If coverage under internals is impossible with the equipment, the method will still be useful for tanks without such internals, or, alternatively, a statistical approach may be allowed, such as mentioned above;

The spread in TRL of available technology is wide:

- There are online inspection robots with a proven track record providing inspection of crude tanks, albeit with limited capability and coverage (TRL 7/8/9);
- There are new robots entering the market providing 90% coverage with a better inspection capability for wall loss, as well as floor elevation (TRL 5/6);
- Some relevant technologies require engineering-type of development, such as orientation with sonar, floor elevation measurement and crack detection of welds. These have an estimated TRL of 4/5;
- Some relevant technologies require more fundamental development, including leak detection of welds and coating condition measurement, resulting in an estimated TRL of 1;
- There may be opportunities to enhance Acoustic Emission testing on tanks (corrosion activity and leak detection) by placing sensors in a tank with an online robot.

A condition of these visions is that the tank is clean. This means that this technology can only be applied in tanks containing product that is sufficiently clean, or online cleaning is a prerequisite.

### A.5.5 Online autonomous inspection of uncleaned tank

Autonomy added to an online inspection robot may give small incremental improvements on top of operator-controlled operation. Such a development will likely affect costs, possibly remove human error from the inspection process, and may reduce time that personnel is exposed to being on the roof of the tank or near the tank (if that is considered a hazard). Furthermore, since no human operator is needed for operation, time constraints are released. This means that a fully autonomous robot can take much more time for example to substantially increase coverage or accuracy.

Online autonomous inspection of an uncleaned tank either requires the implementation of a means to move deposit out of the way, or an inspection technique that is insensitive to the presence of deposit. TRL and BRL are 1, business impact 3 (assuming online inspection was in place already).

\(^{19}\) This statistical approach is currently used for offline inspections with screening methods of which the POD is too low for definitive assessment of the state of the asset
A.5.6 **Online repair**

It is estimated that only 20% of the inspected Aboveground Storage Tanks definitely require repair. In other cases, repair patches are applied as a pre-emptive measure to reduce the risk of unplanned future repairs.

For these 20%, avoiding human entry and taking the asset offline for inspection would have no effect if in order to execute the repair the tank still has to be taken offline and prepared for human entry. Given the costs of taking the tank offline, the business impact of avoiding this is estimated to be level 4. This situation can only be reached if online repair is possible. Both at level 1, TRL and BRL are still very low.

### A.6 Overview and Summary of the Visions

The visions presented in the previous sections form a more or less logic staircase from ‘dreams’ (TRL/BRL = 1) to ‘almost there’. Online remote cleaning has value on its own, as this is sometimes needed irrespective of inspection. It is a pre-requisite for other (online) solutions.

The below table summarises the potential of the various visions: impact versus TRL and BRL.

<table>
<thead>
<tr>
<th>Vision</th>
<th>TRL</th>
<th>BRL</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>offline autonomous inspection</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>offline remote inspection</td>
<td>6</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>online remote cleaning</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>online repair</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>online inspection clean tank</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>online autonomous inspection / uncleaned tank</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>
Or, in graphical form:

![Innovations Landscape Map AST](image)

Legend:

- ![in service](image)
- ![out of service](image)
A.7 Capability Gaps

The following gaps are present between the current capabilities and those required to realise the long-term visions:

- Robot in in-service tank (explosion proof equipment, launching process);
- Accurate localization and navigation in product;
- Autonomous operation in tank with appurtenances;
- Robotic crack detection in HAZ around welds;
- Robotic crack detection in welds, including the welds connecting the wall to the floor;
- Robotic measurement of floor inclination;
- Robotic inspection of supports and other appurtenances;
- Umbilical management to avoid entanglement in appurtenances (or wireless operation);
- Robotic cleaning in in-service tank;
- Robotic inspection of coating;
- Automated processing of (high volume) inspection data;
- Robotic in-service repair.

Depending on the application and/or the solution chosen, some gaps may be ineffective. For instance, in clean product, robotic cleaning is not an effective gap.
Appendix B Pressure vessels

This appendix presents the roadmap for inspection and maintenance of Pressure Vessels (PV).

In the first section the main characteristics of PVs are presented. The three following sections sketch the requirements for operation, the functional requirements for inspection and maintenance, as well as the current inspection and maintenance practice.

This is followed by a section about the critical tasks of inspection and maintenance in the light of the asset operator’s drivers: these tasks impact safety, operational efficiency and the environment the most. The next two sections present the actual roadmap: section 4.6 presents the visions and possible solutions, while section 4.7 gives an overview of the visions in the format of a bubble graph. The last section lists the most important capability gaps between the visions and the current status quo.

B.1 General background

Function of Pressure Vessels
Pressure Vessels (PV) play an important role in the petroleum and (petro)chemical process industry.

Examples of Pressure Vessels
Their uses include:

- Storage of liquids and gasses;
- Generation of (pressurised) steam, in boilers;
- Filtering and separation;
- Processing (chemical reactions); and
- (Fractional) distillation²⁰.

Construction materials include those listed below:

<table>
<thead>
<tr>
<th>Construction</th>
<th>Petro</th>
<th>Chem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Steel (CS)</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>Cladded CS: a CS PV gets a relatively thin (several mm) liner of another metal, often Stainless Steel (SS). The cladding layer can be applied with for example explosion welding. The purpose of the cladding layer is protection of the CS body against the contained product</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>SS, used for aggressive products</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>CS with liner tailored to product contained</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Fibreglass-reinforced plastic (FRP)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Dual laminate, which is a hybrid system made of a specialised thermoplastic liner on the inside and a FRP structure on the outside. The liner can be matched to specific chemical requirements</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>HDPE, PE</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

²⁰ © illustration Ibartman: http://lbartman.com
Usually, PVs have one or more manways to enable human access for inspection and maintenance as well as several nozzles for connecting piping for input and output of products. Depending on the function, PVs often have internal components, including:

- Vortex breakers, to avoid the eroding effect of inflowing product. These can have many forms;
- Separators;
- Plateaus (for instance in a distillation column);
- Spargers;
- Stiffeners (beams and rings);
- Components for catalysts.
Working pressure and wall thickness
Pressure Vessels operate at a pressure anywhere from <1 Bar ('underpressure') to hundreds of Bar overpressure. Design and manufacturing are subject to special regulations. In order to be able to cope with high pressures, the wall thickness may be more than 10% of the vessel's diameter. In the Petroleum industry, the wall thickness usually has a significant corrosion allowance. In the (petro)chemical industry, often PVs have a liner that protects the construction against the harsh nature of the product, and corrosion allowance may be much less.

Working temperature
The working temperature of pressure vessels may be substantially higher or lower than the environmental temperature. In those cases insulation is present, in order to maintain energy and the correct process conditions. The insulation is designed to prevent water ingress (rain). High humidity inside the insulation may lead to Corrosion Under Insulation (CUI). This is dangerous, since it may progress unnoticed and very rapidly. Therefore a visual check of the insulation is performed periodically.

Catalyst
Many processing units in the petroleum and (petro)chemical industry include one or more units that contain catalyst. Although in principle catalyst is not used up in a chemical reaction (it rather facilitates the reaction), small amounts of it are lost in the process. Because of this, catalyst needs replacement at regular intervals, for example at 2 year intervals. In practice this dictates the rhythm of inspection and maintenance. For catalyst replacement the asset always must be taken offline and opened. Catalyst is quite rare in the Oil & Gas industry.

B.2 Requirements for PV operation
The operator’s requirements for PV operation, as far as relevant for this roadmap, include:

- Being able to operate the PV safely, continuously and predictably;
- Having up-to-date asset condition information (corrosion map of the wall, condition of the welds etc.) to maintain the asset efficiently. Condition assessment intervals and details may depend on the product contained, historical trends in the asset’s condition, the risk involved, RBI-analysis et cetera;
- Minimising downtime needed for inspection, cleaning and maintenance. Under certain circumstances it may be advantageous to be able to execute all condition assessment, and ultimately all maintenance while the asset remains in service. Required downtime should be planned well ahead;
- Minimising the risk of unplanned maintenance.

21 If for instance the catalyst replacement interval is 2 years and the maximum inspection interval is 5 years, an inspection is executed during every second catalyst replacement (every 4 years)
22 Either in graphical or textual form
B.3 Functional requirements for PV inspection

PVs are inspected according to the following functional requirements:

1. Wall:
   a. required coverage: 100% or as close to this as possible;
   b. defect mechanism: corrosion, to be assessed:
      i. Type (pitting, general wall thinning);
      ii. Remaining wall thickness;
      iii. Dimensions and location of corroded patch;
   c. damage to the liner, caused by product;

2. Welds and Heat Affected Zone (HAZ):
   a. Coverage: 100% or as close to this as possible;
   b. Defect mechanism: cracking, to be assessed:
      i. Location and length;

3. Internal components:
   a. Inspection of material and welds;

4. Insulation:
   a. Integrity of the insulation;
   b. Leakage.

Inspection of the wall, welds and HAZ are related to safety, and thus will usually need to obey regulations and law. Inspection of internal components in general relates to the correct functioning of the equipment and the production process, and thus is not regulated\(^3\).

\(^3\) Safety may implicitly be involved, though, in which case it may be regulated
B.4 Current practice and available techniques

Currently PVs are inspected internally as follows:

1. The inspector enters the vessel and performs a General Visual Inspection (GVI);
2. Suspect locations (as based on the GVI) are subjected to Close Visual Inspection (CVI);
3. Welds are inspected for cracks (CVI);
4. Nozzles and their welds are inspected (CVI);
5. Known indications are inspected for progression;
6. Where necessary, other than visual techniques may be used, such as Ultrasound Testing (UT), Eddy Current (EC), Dye Penetrant (DP), Magnetic Particle (MP) inspection and so forth;\(^\text{24}\);
7. Internal components are inspected by an Operations & Maintenance inspector;\(^\text{25}\);
8. Insulation, if present, is inspected visually from the outside (which may lead to focussed follow-up inspection).

\(^{24}\)UT is often used for wall thickness measurements, sometimes for crack detection and other assessment. EC, DP and MP may be used for crack detection.

\(^{25}\)This is usually a different person, whose work is not safety related, but functionality related.
B.5 Critical tasks

The tasks in PV operation/inspection/maintenance that are currently on the critical path are identified as follows:

1. Emptying the PV;
2. Flushing, for instance with hot water;
3. Isolation of the vessel;
4. Removal of remaining debris and additional cleaning if needed 26;
5. Internal inspection 27;
6. [removal of insulation 28]
7. [catalyst replacement 29]
8. Repair. If inspection reveals significant damage, the vessel needs repair (or even replacement). Repair can take the form of welding, re-coating, replacing internal components et cetera.
9. Re-connection of the vessel
10. [re-application of insulation]

Preparation and human entry

the asset must be taken offline. The remainder is used for preparation such as cleaning and isolation. Up to 80% of the total offline time is spent on activities that are solely needed for human entry of the vessels. Hence avoiding the need of human entry can reduce the inspection-related costs and increase safety very significantly.

Catalyst

periodically taken offline and cleaned for catalyst replacement. Inspection is synchronised with this rhythm. This means that reducing inspection related impact by avoiding human entry of the system is only effective in such cases if the same actions can be avoided in the context of catalyst replacement. In those situations catalyst replacement must also be carried out robotically.

If online inspection is pursued for a system in which catalyst plays a role, online catalyst replacement must also be developed.

The solutions presented in the next sections all aim for reducing the impact of one or more of the tasks listed above, either by decreasing the time needed to perform such a task, or by removing the execution of the task from the critical path. Some of these solutions follow parallel tracks but there are differences in time frame.

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26 This largely depends on the nature of the product and of the maintenance works needed. For example, an extra cleaning operation may be needed in case of toxic product. If heat inducing maintenance works are needed (welding, cutting) and
27 Often, the internal inspection itself does not take more than 15-30 minutes, and so strictly speaking is often not on the critical path. If extensive follow-up inspection is needed, the inspection may become on the critical path
28 Obviously, this is only needed for insulated vessels, and where access to the outside of the vessel’s wall is needed for inspection purposes or for access to nozzles, manways and such. In case access to the external wall is needed at a very specific location that is exactly
29 Catalyst is typically only used in the (petro)chemical industry
B.6 Visions

This section presents the vision that were formulated during the SPRINT Programme Committee and Participants workshop in Kopervik, Norway, December 2016.

B.6.1 Non-Intrusive Inspection

Non-Intrusive Inspection (NII) techniques use methods to inspect the vessel without entering it. Currently available methods to determine the wall thickness from the outside of the vessel include UT, (Pulsed) Eddy Current and Acoustic resonance. Some UT techniques are in principle capable of detection of internal cracks from the outside.

NII in these scenarios centres on the inspection of the wall and the nozzles, so on the safety-related elements. In general full external inspection of internal components will not be possible, although in certain cases inspection of the welds that attach the component to the wall may be feasible.

The following variations of NII are previsioned:

1. Out of service external inspection of wall and nozzles of an uninsulated vessel. The vessel is taken out of service and insulation material removed, if applicable. The vessel wall is directly accessible for the inspection. Techniques that are currently used in a different context can be used here, hence a TRL of 4;

2. Out of service external inspection of wall and nozzles of an insulated vessel. Since the vessel wall is hidden underneath the insulation, the inspection technique must either be capable of inspecting through the insulation (like for instance Pulsed Eddy Current), or be deployed by a robot that resides between the insulation and the vessel wall. The TRL is set to 1, since a very significant technical development is required;

3. In service external inspection of wall and nozzles of an insulated vessel. This case is similar to that of item 2, but the high (or low) temperature adds complexity. Hence the TRL is set to 1.

For all of these NII scenarios, the business is nearly ready, resulting in a BRL of 6.

B.6.2 Opening manhole but no human entry (no vessel isolation)

If a vessel is taken out of service and its manhole (or a nozzle) is opened, it can be inspected from the manhole or nozzle without human entry. The inspection can take place using one or more robots. Current developments along these lines include arm robots, snake robots, crawlers and flying robots equipped with a camera or sometimes with UT. Combination with other NDE techniques is expected to be closer to the horizon. The added value of this approach as compared to human entry will arise from:

- The removal of the requirement to isolate the vessel;
- Reduction of cleaning requirements.

If the location to be inspected is exactly known up front, a plug can be made in the insulation to remove the insulation very locally and temporarily. Operation of the vessel need not be interrupted for this.
The technical developments to make this approach possible are well under way, resulting in an estimated TRL of 7. The business readiness level is 7 for the first applications. The impact will be high: impact level 4.

B.6.3 Nanobots in the product

One day, nanobots, or simply ‘very small robots’, are supposed to be able to operate in the product without interfering with the functioning of the equipment. They would either reside permanently in the product or be inserted into and extracted from the product without interrupting the processes. In principle they could ‘go with the flow’ of the product or be able to independently move and navigate in the product, even against the direction of the product flow. In the case of permanently resident nanobots, facilities must be present in the vessel for recharging the nanobots’ batteries and for data exchange with ‘outside’. Nanobots may operate 24/7 and be present in large numbers, which would open up the approach of unorganised scanning the vessel, reaching full coverage because of the large number of scanning movements and random nature of the movements.

Although crawling, swimming and flying nanobots do exist, very significant hurdles must be cleared before they are thought to be able to play a role in equipment inspection in the petroleum and (petro)chemical industry. Also equipment will most likely need adaptation for use of nanobots, for instance insertion and extraction points and recharging and communication facilities will be needed. Incorporation of the new inspection data in the assessment process may require changes to the approach. Statistics may need to play a more important role. Hence the TRL as well as the BRL are estimated to be 1.

B.7 Overview and Summary of the Visions

The visions presented in the previous sections are on average characterised by a relatively low TRL. Higher TRL robotic solutions (TRL4 and up) are only provisioned for uninsulated vessels (or vessels that have had their insulation removed prior to inspection).
The below graph summarises the potential of the various visions: impact versus TRL and BRL:

**Legend to the above graphic:**
- ![in service, insulation](image)
- ![out of service, insulation](image)
- ![in service, no insulation](image)
- ![out of service, no insulation](image)

**Or, in table form:**

<table>
<thead>
<tr>
<th>Vision</th>
<th>TRL</th>
<th>BRL</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>NII out of service external inspection of Wall and nozzles, no insulation</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>NII out of service external inspection of Wall and nozzles, insulated</td>
<td>1</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>NII in service external inspection of Wall and nozzles, insulated</td>
<td>1</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>opening manhole but no human entry (out of service, no vessel isolation)</td>
<td>7</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>nanobots put into the product</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

---

31 Bubbles in bottom left corner were marginally shifted for displaying purposes
B.8 Capability Gaps

The following gaps are present between the current capabilities and those required to realise the long term visions:

- Capabilities of crawlers to traverse complicated internal components;
- Wall thickness measurement and crack detection through insulation (including pitting corrosion);
- Detection from the outside of cracks on the inside of the wall;
- Combination of small diameter snake or robot arm with long reach, high dexterity and substantial payload;
- Robotic crack detection in welds and in the HAZ around welds;
- Nanobots suitable for online inspection;
- Nanobots to inspect in space between vessel wall and insulation.

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32 For inspection through small bore nozzles for inspection in otherwise inaccessible compartments in vessels
33 Including recharging and communication stations. ATEX zone 0 or 1 will be required
34 ATEX zone 0 may be required
Appendix C Process piping

The first section of this chapter characterises process piping and specifies the scope of the roadmap for this subject. This is followed by a description of piping operation, inspection requirements and current practices. After this the critical tasks are identified. The chapter ends with the formulation of visions for inspection and maintenance of process piping and the identification of capability gaps.

C.1 Piping characteristics and scope

The subject of this roadmap chapter is ‘process piping’ in the petroleum and (petro)chemical industry. Process piping is defined as the piping interconnecting vessels, tanks and other equipment in a processing plant. The contents of the piping may be hot, cold, pressurised, toxic, acid, alkaline et cetera. Pipes may be insulated. Pipe materials include CS and composite.

For the purposes of this roadmap the following categories are included in process piping:

- The piping, transporting fluids, gasses and powders related to the processes;
- Flanges and fittings;
- Pipe support areas;
- Valves;
- Joints, bends and elbows;
- Expansion loops and pipe bridges;
- Pipe racks.
Excluded are:

- Transport pipelines;
- Heat exchangers;
- Construction tubing.

Piping comes in several, very different forms:

- Single pipes;
- Multiple pipes. These are often close together (such as in pipe racks), limiting access for inspection and maintenance;
- Pipe bridges: overspanning a road;
- Buried or in a tunnel.

**C.2 Requirements for piping operation**

Process piping operating requirements include:

- Containment of the fluids, gasses and powders under all circumstances;
- Often: thermal insulation, either as energy conservation or to keep the contents under the correct conditions (viscosity, process temperature, avoid polymerisation et cetera);
- Absorbing thermal expansion. This is generally achieved by means of expansion loops or expansion joints;
- Steering process streams, generally by means of valves.

**C.3 Requirements for piping inspection**

Process piping inspection requirements are specified in standards such as ASME B31.3, ISO 13703 and API 570.

**C.4 Current practices and available techniques**

Current practices of process piping inspection include:

- Removal of insulation at selected locations, followed by visual inspection and wall thickness measurements with for example UT pulse echo. Removal (and renewal) of insulation is very costly and is only be executed on selected locations;
- CML: Corrosion Monitor Location inspection. For this inspection method certain locations are marked at which periodically the remaining wall thickness is measured, usually by means of UT. This method enables determination of a trend in wall thickness change. It is suitable for situations where a slow and even decrease in wall thickness is expected, or where the expected location of wall thinning is well known, such as acid content in crude oil that leaves a corrosion track at the six o’clock position in the pipe.
Robotising/automating basic CML is thought to have very high, or even the highest, impact, since it is applied very often and most money is spent here. It would need to be repeated often, for insulated as well as uninsulated piping;

- Internal inspection, usually from an open flange (which is usually opened for the inspection);
- Guided wave inspection. In this type of inspection acoustic waves of relatively low frequency are used which can travel over dozens of meters. Reflections are a measure for wall thickness changes (and more);
- PEC, or Pulsed Eddy Current, an electromagnetic method able to measure wall thickness of ferro-magnetic pipes through insulation;
- Thermography and neutron backscatter. Both these techniques detect humidity in the insulation, a precursor for Corrosion Under Insulation (CUI);
- Visual inspection, of insulated as well as of uninsulated pipe, for traces of corrosion and, in the case of insulated pipe, leaking and damaged insulation.

Often these techniques require scaffolding to be erected (and removed afterward), which is expensive and time consuming. The same holds for removal and renewal afterward of insulation.

C.5 Critical tasks
The critical tasks in piping inspection include:

- Scaffolding: this is time consuming and expensive;
- Removal and renewal afterward of insulation: this, too, is expensive and time consuming;
- Opening flanges for inspection. Before a flange is opened, the installation must be taken offline and be cleaned thoroughly. Offline costs due to interruption of production are often dominant.

C.6 Visions
The following visions have been developed for piping inspection.

C.6.1 Climber/arm/drone to remove need for scaffold around elected sections
Costs can be avoided and safety increased by removing the need for scaffolding. The same NDE methods can be used as those used at present, but the deployment can be changed in order to avoid the need for scaffolding. Much of the basic robot equipment is available. If a cherry picker or comparable is needed, road access is needed. Suitable robotics include drones and crawlers.

C.6.2 Offline Internal inspection (visual)
Current internal piping inspection, with access through for example open flange, can be made more efficient and powerful by using advanced robotic deployment. Future developments (tetherless operation, improved dexterity and manoeuvrability etc.) can significantly improve the inspected
distance and reachable pipe sections and thus result in a significant (medium) impact. Most of the insulation can remain installed.

C.6.3 Offline Internal inspection (WT)

See section C.6.2, but now with equipment for WT mapping (high coverage). This will reveal and size internal as well as external corrosion (CUI). Hence the impact may be high.

C.6.4 external CVI

External visual inspection can reveal external corrosion and coating damage ( uninsulated piping) and detect possible CUI through leakage traces and wet insulation. For many applications drones and (thermal) cameras are available, hence the TRL for first applications is high. In the not too far future this can be made autonomous (flying + automatic image interpretation), which opens the possibility of much more frequent inspection and trending. Accessibility in case of dense pipe rack may be problematic, but this can be solved with more specialised crawlers, snakes et cetera.

C.6.5 External wall thickness measurement of internal fouling, scaling

External wall thickness measurement of internal fouling and scaling can be done with UT and with various electro-magnetic techniques. Deployment can be with various types of robots, ranging from arms to crawlers to microbots, the latter even in swarms, and possibly underneath insulation.

C.6.6 Online internal inspection

Online internal inspection requires either robots that can be inserted into the process stream and extracted later (at the same or a different location), or resident robots. The latter must be able to recharge inside the processing equipment and to communicate relevant data with the outside world. Development of such applications is still in its infant stages, although a number of basic elements are available. The impact of such technology would be huge, since system down time and scaffolding are avoided and insulation can remain in place. Furthermore inspection can be frequent.

C.6.7 Inspection of insulation with NDE (non visual)

There are NDE techniques that are capable of detecting humidity inside insulation (such as thermography and neutron backscatter). Wet insulation is a precursor of CUI. Thermography is currently sometimes executed by means of a drone. This should be made autonomous. Improved control will make inspection in more dense pipe racks possible. Neutron backscatter is currently applied with a sensor on a stick, which results in highly limited reach and coverage. Robot deployment of the sensor would improve coverage significantly.

C.6.8 Inspection through insulation - Corrosion mapping

NDE methods for WT mapping through insulation include PEC, RT radiography (to a certain extend) and acoustic resonance. Robotic deployment will largely increase coverage and reduce costs of scaffolding, as compared with current application of these methods.
C.6.9 Support inspection: simple, clamped, spring loaded: ultrasound, guided wave

Various ultrasound techniques can be used for remote inspection, including multiskip, guided waves, lamb waves. These are all contact techniques, i.e. one or more UT sensors need to be in contact with the pipe material. This can be done by a robot after (robotic) removal of the insulation at the relevant location. After the inspection the insulation must be re-mounted.

C.7 Overview and summary of the Visions

The visions described in the previous section are summarised in below table.

<table>
<thead>
<tr>
<th>Vision</th>
<th>TRL</th>
<th>BRL</th>
<th>IL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climber/arm/drone to remove need for scaffold around elected sections</td>
<td>5</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Offline Internal inspection (visual)</td>
<td>7</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Offline Internal inspection (WT)</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>external CVI - insulated + uninsulated (Drone/camera)</td>
<td>8</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>External wall thickness measurement of internal fouling, scaling</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Online internal inspection</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Inspection of insulation with NDE (non visual)</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Inspection through insulation - Corrosion mapping</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Support inspection: simple, clamped, spring loaded: ultrasound, guided wave</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
And below the same information in graphical form:

Innovation Landscape Map Piping

Legend:
- **in service**
- **out of service**
C.8 Capability gaps
Currently the following capability gaps are present that have to be closed to realise the above presented visions:

- Navigating visual sensors ('visual' or thermographic camera) close to piping in dense pipe rack or piping close to other obstructions;
- Crawling over piping in the presence of obstructions (for instance other piping) in order to bring sensors to selected locations and optionally execute scanning. Sensors may include (contact or resonance) ultrasound sensors, guided wave sensor rings, PEC sensors et cetera;
- Crawling over insulated pipe. The outer casing of the insulation may be either ferro-magnetic or not (often plastic in the latter case);
- Robotic removal and re-mounting of insulation;
- Robotic removal and re-mounting of CML plugs;
- Mounting a guided wave ring on a pipe;
- Autonomous navigation and inspection in a complicated environment;
- Automatic interpretation of inspection data in case of autonomous and frequent inspection.
Appendix D Remote Operator

D.1 Scope

In short, a remote operator can be defined as any application of a robot where it replaces a human operator for a substantial task. The robot may be fully or semi-autonomous, or may be remotely operated. Reasons for wishing to replace the human operator by one or more robots include:

- Cost efficiency, such as on a platform or remote site;
- Safety, such as when responding to an alarm;
- Performing repetitive tasks at a high quality level.
In the context of this roadmap the following roles are considered:

1. **First responder**: sent out in reaction to an event
   - **Purpose**: remove human observer from potentially dangerous situation;
   - **Purpose**: unmanned facilities: avoid the need to go there (time, costs, safety);
   - **Assess conditions and react**;
   - **See, smell, listen (incl. ultrasound)**;
   - **IR camera, gas detector, wind (direction) sensor**;
   - **[radiation detector]**;
   - **Clearing alarm and reporting back**;
   - **press buttons etc. (re-start operation after emergency shut-down)**;
   - **[Operating valves, see below]**.

2. **Emergency response**
   - Manned and unmanned platforms and sites;
   - All functions of the First Responder;
   - Rescue people;
   - Fire fighting.

3. **Regular Operation – daily tasks**
   - Walk around, check, read dials, see if anything has changed, smell, listen;
   - Raise warning or alarm flag when appropriate;
   - Gas detection;
   - Sample taking (gas, liquid (process, dripping/spill), wipe, …); analysis is performed in lab afterward (not by operator or robot).

4. **Other, including**:
   - Cleaning (dirt, corrosion, safe landing platform);
   - Chase away birds.

‘Operating valves’ is a difficult task which requires a strong, and thus heavy and big, robot and an anchoring point. This is in contrast with many other frequent tasks, most particularly monitoring, which only requires a small, light and cheap robot. Hence the requirement to operate valves must be carefully considered per application.

Sub-sea work is excluded from this roadmap (for now).
Some other aspects in this context are:

- The robot must be able to work indoor as well as outdoor, and may have to be able to open (and close) doors;
- The robot must use the infrastructure that is available. No special infrastructure, such as rails, staircases and manways, must be built or adapted to enable the remote operator;
- The robot must be able to safely work in the presence of people without significant requirements for their behaviour;
- ATEX or IECEx certification will be required;
- Multiple robots may be needed to fulfil any of the above described roles.

D.2 Current practices

Currently the roles described in the previous section are fulfilled by human operators and specialists:

- A plant operator makes a periodic, often daily, round to report any unexpected changes, like smells, leakages, damages, rust water traces. He will take process samples, read dials etcetera. All of these actions are quite predictable and repetitive;
- If a warning or an alarm is raised or anything else seems out of the ordinary, a first responder (operator) will react to the event. He will take samples of leaked fluid and perform many of the tasks mentioned above. He will assess the conditions in any way appropriate and he will determine the wind direction (which may become relevant in case of an evacuation). In case this type of event occurs on a remote or offshore site, a human operator needs to travel to the site, e.g. by helicopter, which is very expensive. The plant or part thereof may have been shut down in response to the event, in which case a restart must be initiated. Many, if not all, of these actions are standard, but if and when they are executed depends on the situation. A certain amount of improvisation may be required;
- In case of an emergency, everything depends on the situation. A fire may need to be extinguished, a person may need first aid and or evacuation, the plant may need to be shut down, leakage controlled. A specialised crew may need to travel to the site and the location in question, which may be time consuming (hence postponing the counteraction, which may worsen the emergency) and expensive. Furthermore, considerable risk may be involved with emergency response.
D.3 Visions

The level of autonomy needs careful consideration. First responder and emergency response should remain under direct human operator control at all times, where at most the human operator delegates certain standard tasks to be executed autonomously (i.e.: the robot acts semi-autonomously or is remotely operated). The reason for this is twofold:

- First and emergency response functions are by nature not standardised. A certain level of creative improvisation will always be needed. Some basic functions can be standardised, though, such as moving to a given location, taking samples et cetera;
- The number of occurrences of first response and emergencies are too low to enable a robot to learn to take the proper actions.

Regular operation tasks may be executed autonomously by the robot, as these are rather well defined and predictable. Furthermore they are thought to be needed frequently, so that the effort needed to develop autonomy will be outweighed by the potential gain.

The next sections present the visions for the Remote Operator application. The following abbreviations are used for the different levels of autonomy:

- RO: Remote Operator (no autonomy)
- SA: Semi-Autonomous
- FA: Fully Autonomous

D.3.1 Operation RO – Monitoring; flat surfaces

This vision encompasses an Operation robot with the ability to perform monitoring tasks such as sensing: gas, infrared, environment (such as wind force and direction), making camera and (ultra)sound recordings, reading dials and relay this information. Operation mode is ‘remote’. This type of robot is expected to be small and light and relatively cheap.

D.3.2 Operation FA – Monitoring; flat surfaces

This vision equals the one described in the previous section, but is fully autonomous. Since the tasks involved are executed frequently, the impact of autonomous operation is significant.

D.3.3 Operation FA – Monitoring; all environments

This vision equals the one described in the previous section, but is capable of negotiating all practical environments, including staircases and cage ladders. Therefore it would also be suitable for remote and unmanned sites.

D.3.4 Operation RO - Complex tasks

This remotely operated robot is capable of more complex and heavy tasks, such as moving obstacles, carrying payload and opening doors. Certain tasks may require a dedicated robot, for
instance carrying payload. This type of robot is expected to be much larger and much more powerful, and hence more complex and expensive.

**D.3.5 First Responder SA – Visual, sensors, remote restart; all environments**

The main capabilities of the robot in this vision are traveling in any environment, including staircases and cage ladders, gathering and relaying information and pushing a button (restart). The information to be gathered is visual as well as sensor information (gas, wind, infrared, radiation, (ultra)sound etc.). The operation mode is semi-autonomous: an operator is in control and commands the robot to perform certain tasks autonomously. This robot is supposed to be suitable for remote and unmanned sites.

**D.3.6 Cleaning SA**

Cleaning is needed for correct and safe functioning of a plant. There exists an array of suitable cleaning methods and even cleaning robots, and there exist robots that are capable of negotiating the type of environment needed for these roadmap applications. They need to be integrated and be adapted for this purpose.

**D.3.7 Simple maintenance activities**

Simple maintenance activities include fastening bolts/nuts, perform simple temporary repairs to postpone planned repair by a human repair crew (that in certain applications needs to be flown in), permanently/temporarily repair insulation et cetera.

**D.4 Overview and summary of the Visions**

The following table summarises the visions and specifies TRL, BRL and IL:

<table>
<thead>
<tr>
<th>Vision</th>
<th>TRL</th>
<th>BRL</th>
<th>IL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation RO - Monitoring; flat surfaces</td>
<td>8</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Operation FA - Monitoring; flat surfaces</td>
<td>6</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Operation RO - Complex tasks</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Operation FA - Monitoring; all environments</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>First responder SA - all environments</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Emergency RO/SA - fire fighting, evacuate person; staircase</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Cleaning SA</td>
<td>5</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Simple maintenance activities</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
D.5 Capability gaps

The following capability gaps for the realisation of the Remote Operator visions were observed in practical circumstances:

- The ability to climb cage ladders;
- The ability to open/close valves. Some robots have shown the ability to turn a light valve. However, in practice valves rarely run light and considerable force is needed, which requires a strong, heavy robot and an anchoring point;
- The ability to effectively handle and manipulate tools and materials;
- Advanced and full autonomy. This has been demonstrated in other situations, but this has not yet been fully translated to the petroleum and (petro)chemical industry;
- The ability to safely co-exist with human personnel in practical, working plants. Although considerable ability has been shown already to co-exist in public places, this has not yet been translated to the petroleum and (petro)chemical industry;
Appendix E TRL, BRL and IL

The TRL is a measure of maturity of the technology. The European Commission definition of the TRL scale is as follows:

<table>
<thead>
<tr>
<th>TRL</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL 1</td>
<td>Basic principles observed</td>
</tr>
<tr>
<td>TRL 2</td>
<td>Technology concept formulated</td>
</tr>
<tr>
<td>TRL 3</td>
<td>Experimental proof of concept</td>
</tr>
<tr>
<td>TRL 4</td>
<td>Technology validated in lab</td>
</tr>
<tr>
<td>TRL 5</td>
<td>Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)</td>
</tr>
<tr>
<td>TRL 6</td>
<td>Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)</td>
</tr>
<tr>
<td>TRL 7</td>
<td>System prototype demonstration in operational environment</td>
</tr>
<tr>
<td>TRL 8</td>
<td>System complete and qualified</td>
</tr>
<tr>
<td>TRL 9</td>
<td>Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)</td>
</tr>
</tbody>
</table>

The BRL is a measure of the readiness of the business to develop and produce the new technology. The BRL is commonly defined as:

<table>
<thead>
<tr>
<th>BRL</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRL 1</td>
<td>Inventor (or team) with a dream</td>
</tr>
<tr>
<td>BRL 2</td>
<td>Paper studies and analysis produced</td>
</tr>
<tr>
<td>BRL 3</td>
<td>Capability for conducting laboratory experimentation</td>
</tr>
<tr>
<td>BRL 4</td>
<td>Capability to work limited-scope R&amp;D programs with project teams</td>
</tr>
<tr>
<td>BRL 5</td>
<td>Capability to support project engineering development and design</td>
</tr>
<tr>
<td>BRL 6</td>
<td>Capability to support development and design with a market-driven business team</td>
</tr>
<tr>
<td>BRL 7</td>
<td>Capability to support limited production; full business team</td>
</tr>
<tr>
<td>BRL 8</td>
<td>Capability to transition to full production and distribution</td>
</tr>
<tr>
<td>BRL 9</td>
<td>Fully articulated business with appropriate infrastructure/staffing</td>
</tr>
</tbody>
</table>

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35 European Commission, Horizon 2020, Technical annex G, following closely the original 1989 NASA definition
36 BRL does not have such a clear source as TRL. However, the definition and scale given is regularly encountered and suitable for use in this context of roadmapping.
The impact a new technology is thought to have on the (end) user is expressed as Impact Level (IL), which in this roadmap is defined as follows:

<table>
<thead>
<tr>
<th>IL</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL1</td>
<td>Satisfies very little of the business drivers, has little to no impact</td>
</tr>
<tr>
<td>IL2</td>
<td>Satisfies some of the business drivers, but the impact is minimal</td>
</tr>
<tr>
<td>IL3</td>
<td>Satisfies most of the business drivers, but has medium impact</td>
</tr>
<tr>
<td>IL4</td>
<td>Satisfies most of the business drivers, the impact is large</td>
</tr>
<tr>
<td>IL5</td>
<td>Satisfies all of the business drivers, and the impact is overwhelming</td>
</tr>
</tbody>
</table>
# Appendix F Contributors

The following companies and persons have contributed to this roadmap by attending one or more workshops and/or providing feedback:

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<td>SGS</td>
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<td>Aksel Transeth</td>
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