

Robotic Solutions for Inspection and Maintenance on  
Unmanned Facilities

Christoffer Grytøyr

Autumn 2019

Department of Engineering Cybernetics  
Norwegian University of Science and Technology

# Preface

This is a pre-study for a Master's thesis as part of the study program Industrial Cybernetics at NTNU. The project accomplished during the autumn semester of 2019. The project has been carried out for SUBPRO in cooperation with Equinor, who has put their personnel and assets available for guidance and testing. It is assumed that the reader has a basic understanding of maintenance concepts in the petroleum industry.

Trondheim, 2019-12-31

Christoffer Grytøy

## **Acknowledgement**

I would like to thank Mary Ann Lundteigen, my supervisor from NTNU and SUBPRO connection, and Erling Lunde and Gunleiv Skofteland from Equinor for all their help and effort facilitating this pre-study.

Thank you to all the participating interview subjects from various SUBPRO partners, your input was invaluable.

C.G

# Abstract

This project was started by SUBPRO, on request from Equinor, to analyze the possibilities of robotized inspection and monitoring on unmanned topside facilities, both autonomous and automated.

The objective was to map which technologies are used to today for inspection and maintenance as well as finding technology gaps that needs to be filled to achieve autonomous inspection and maintenance. Further, pointing out which tasks can be done by robots in the future and if there is any special technical or standard requirements that are needed.

A literary study of condition monitoring and inspection methods were done. Inspection methods possible for movable robotics was especially emphasized. A series of interviews with industry partners were conducted to understand the needs and requirements for achieving more autonomy in inspection and maintenance. Further, their view on today's challenges and obstacles for a leaner and more effective inspection scheme were examined.

It was found that robotics could take over inspections tasks such as gas detection and surface monitoring using NDT methods, as well as tasks such as coating and maintenance in confined spaces. Standardizing of equipment and governmental guidelines is a great need for implementing robotics on unmanned platforms. It was found essential to implement a simplistic and subsea mindset in the design phase.

# Contents

<b>Preface</b>	<b>i</b>
<b>Acknowledgement</b>	<b>ii</b>
<b>Abstract</b>	<b>iii</b>
<b>Figures</b>	<b>vi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	1
1.2 Objective . . . . .	1
1.3 Approach . . . . .	1
1.4 Limitations . . . . .	2
1.5 Outline . . . . .	3
<b>2 Condition Monitoring</b>	<b>4</b>
<b>3 Inspection Methods</b>	<b>7</b>
3.1 Visual inspection . . . . .	7
3.2 Infrared Thermography . . . . .	8
3.3 Ultrasonic Testing . . . . .	9
3.4 Radiography . . . . .	9
3.5 Acoustic emissions . . . . .	10
<b>4 Robotic Solutions</b>	<b>11</b>
4.1 Autonomy . . . . .	11
4.2 Advances in robotics . . . . .	13
4.3 Technology requirements for robotic solutions . . . . .	14
4.3.1 Limitations for implementation of new digital technology . .	15
4.4 Opportunities for robotics in inspection and maintenance . . . . .	16
4.5 Data processing . . . . .	17
4.6 Standard requirements . . . . .	20
4.7 Swarm Robotics . . . . .	21

4.8	Practical case - Taurob Tracker . . . . .	21
4.9	Practical case - Thermography camera experiment . . . . .	24
<b>5</b>	<b>Discussion</b>	<b>27</b>
5.1	Maintenance-heavy equipment on today's facilities . . . . .	27
5.2	Condition monitoring as a tool . . . . .	27
5.2.1	Digitalization of maintenance . . . . .	29
5.3	Inspection of unmanned facilities . . . . .	30
5.3.1	Opportunities for robotic inspection and maintenance . . . . .	30
5.4	Technical and standard requirements . . . . .	32
5.5	HSE . . . . .	33
5.6	Autonomous robotics . . . . .	34
5.7	Economical impact . . . . .	35
<b>6</b>	<b>Conclusion</b>	<b>36</b>
6.1	Further work . . . . .	37
	<b>Appendix A - Main outtakes from interviews</b>	<b>viii</b>

# List of Figures

1	Hierarchy view of main functions in a production platform [14] . . .	12
2	Levels of autonomy in an industry perspective [14] . . . . .	13
3	Data processing and information flow blocks necessary for condition monitoring according to ISO 13374-1 [20]. . . . .	18
4	An illustration of levels and degree of utilization of data through digitalized maintenance [17] . . . . .	20
5	The Taurob Tracker . . . . .	22
6	Control mechanisms of the Taurob Tracker. On the left: The control pad. . . . .	23
7	The Taurob Tracker in drive mode, going up and down stairs . . . .	24
8	Comparison of images finding heat/cold spots when using the thermography camera . . . . .	25
9	The compressor used in this experiment . . . . .	26
10	Pictures taken of the compressor with a thermography camera . . .	26

# **1 Introduction**

## **1.1 Background**

The oil and gas industry is a leading frontier within technology development. Many of the brightest heads have been recruited to push innovation and development further. After an economically challenging period, the industry has taken measures to secure a steady economical growth by initialising an optimization of production, operational expenditure (OPEX) and capital expenditure (CAPEX). One of the measures taken is the implementation of Industry 4.0 technology. This includes the use of AI, robotics, cloud storage and big data analysis. The next big step for the oil industry is combining this technology with safety, environmental and economical improvement.

## **1.2 Objective**

This project was started by SUBPRO, on request from Equinor, to analyze the possibilities of robotized inspection and monitoring on unmanned topside facilities, both autonomous and automated.

The objective is to map which technologies are used to today for inspection and maintenance as well as finding technology gaps that needs to be filled to achieve autonomous inspection and maintenance. Further, pointing out which tasks can be done by robots in the future and if there is any special technical or standard requirements that are needed.

## **1.3 Approach**

Firstly, a literary study of condition monitoring and inspection methods were done. Inspection methods possible for movable robotics was especially emphasized. A series of interviews with industry partners were conducted to understand the needs and and requirements for achieving more autonomy in inspection and maintenance.

Further, their view on today's challenges and obstacles for a leaner and more effective inspection scheme were examined. Some of the main questions posed in the interview were:

1. What systems is the biggest challenge when it comes to maintenance hours and resources?
2. Which technologies are chosen for inspection and condition monitoring for remotely controlled facilities today?
3. What/where are the biggest technology gaps for achieving more autonomy in maintenance and inspection?
4. What are your thoughts on new technology needs?
5. What future possibilities are under development/can be developed for use on unmanned facilities?
6. What manual inspection- or surveillance-tasks can be taken over by robots in the future?
7. What are the technical requirements for it to be possible with autonomous inspection?

The transcribed interviews are attached in Appendix A.

To gain a practical insight in the possibilities for robotized inspection, Equinor's automated robot - the Taurob Tracker - were tested, as well as a practical case study using an IR camera for heat detection. The latter was performed to analyze the possibilities of anomaly detection with equipment made for robotized solutions.

## **1.4 Limitations**

Interviews are anonymized to avoid detection or outing of any individual participant or industrial partner. The interviews are a qualitative and in-depth approach with some key personnel involved in development of inspection and maintenance strategies and solutions. There was not performed a quantitative study, as of this, the interview subjects views may not coincide with all collective beliefs.

## 1.5 Outline

This project delves into theory on condition monitoring and inspection methods suitable for use on robots on remotely controlled or unmanned facilities in chapter 2 and 3.

Chapter 4 depicts the concept of autonomy. Further, it delves into advances in robotics the last few years, as well as looking at technological requirements and limitations/opportunities for implementation of new technology on unmanned facilities. Lastly, two practical cases with equipment for inspection are presented.

Chapter 5 contains a discussion on the main topics, where perspectives from the SUBPRO partner interviews on maintenance heavy equipment, use of condition monitoring, technology gaps and robotic solutions, and implementation on unmanned facilities, from appendix A, are taken into account.

Chapter 6 gives a conclusion to the project as well as recommendations for further work.

## 2 Condition Monitoring

Condition based monitoring (CBM) falls under the category predictive maintenance that was developed in the 70's and 80's to handle the growing complexity in machinery. The complexity led to a lot of equipment not following its predictable age-related failure patterns [1]. Preventive maintenance was therefore not as effective method on these type of systems. Inspections and condition monitoring became more normal as a basis in maintenance, as long as it was technological and economical profitable.

Pintelon and Parodi-Herz [1] emphasizes that predictive maintenance is not just CBM, but a philosophy and attitude that uses real data from the facility to optimize operations. A complete predictive program will use the most cost efficient measuring techniques to plan maintenance as required.

The handbook of condition monitoring [2] describes condition monitoring and maintenance management as a holistic multidiscipline based on systems thinking. It encompasses economics, instrumentation, engineering and scientific disciplines, information technology and management, detection and prediction of faults/failures, diagnostics and prognostics, new maintenance management concepts and legal issues.

Tavner et al.[3] explains condition monitoring as continuous evaluation of a system and equipment through its entire life time. Wilson [4] defines that the purpose of condition monitoring is to detect signs of degradation and offer a measure of degree and speed of the degradation.

Condition monitoring is also covered by several standards. IEC 60050 [5] defines condition monitoring as obtaining information about physical state or operational parameters. NS-EN 13306 [6] defines it as an activity performed either manually or automatically, intended to measure at predetermined intervals the characteristics and parameters of the physical actual state of an item. The same standard defines condition based maintenance as preventive maintenance which include assessment

of physical conditions, analysis and the possible ensuing maintenance actions.

ISO 13372:2012 [7], which is a standard for condition maintenance for machines, defines condition based maintenance as predictive maintenance performed as governed by condition monitoring programmes. The standard defines condition monitoring as acquisition and processing of information and data that indicate the state of a machine over time.

Whether “predictive maintenance” or “condition monitoring” are used, both are terms that refer to proactive inspections with the same goal; to note a deviation from a normal or baseline condition in order to determine whether or not to take corrective action in a planned orderly manner and to prevent an unplanned incident. The ideal end result is to maintain asset availability, reduce maintenance overhead and improve safety conditions. The incorporation of multiple technologies in inspection procedures is important to assure reliable results, as one technology can not cover everything.

According to ISO 17359:2018 [8], the goal of condition monitoring should be to find the underlying cause of the failure mode. I.e. it is not good enough to measure that an equipment is vibrating, but that a combination of measurement parameters, and analysis of these, shall give an indication of the deviation cause.

A simple illustration of condition based maintenance is to fill oil in a car engine. Every time it is filled, how much oil was filled is written down. If this amount increases over a period, then there is a negative trend that can be reacted to. This is equivalent to a change in measurement parameter. Diagnostics tests can be performed based on the state change to find the cause. Implementing some visual inspections, i.e. looking for oil spill under the car, yields more basis for diagnostics.

A questionnaire done in a master thesis [9] about the potential for condition monitoring in a power plant. showed that when asked about requirements for introducing condition monitoring, 80 % responded that it needs to be user friendly and reliable, 70 % said it needed to contribute to troubleshooting, 60 % that it has to be accurate and 50 % answered that it has to be informative, be able to do analysis and communicate with other ICT-systems (Information and Communication

Technology).

There are 3 models for condition monitoring:

- Knowledge based: Based on experience and good familiarity to a system or equipment can such a model capture the expected characteristics. This requires input from specialists. Expanded FMECA with symptoms can be employed.
- Physics based: Based on design and run on physical laws, first principle models that monitor degradation with selected equations i.e. vibration, wear, lifespan, performance etc.
- Data driven: Represents observed behaviour without special knowledge of the physical conditions. Uses patterns and looks for connections that represents decrease in performance. The models are normally automated and need training.

### 3 Inspection Methods

Many Non Destructive Testing (NDT) methods are utilized for inspection in the oil and gas industry. The best NDT methods address issues regarding safety, equipment reliability, and environmental protection and government regulations. The greatest benefits that NDT service provides are

- Equipment for transporting petroleum products can be inspected without making any structural changes.
- Equipment is not disturbed during NDT; therefore there is neither a reason to shut down nor to interrupt operations.

Popular NDT methods involve visual inspections, ultrasonic techniques, radiography, thermography, laser shearography, eddy current testing, microwaves, and acoustics.

Robots are playing an increasingly important role in all manner of inspection and maintenance practices, ranging from simple visual inspection to complex non-destructive testing/evaluation(NDT/E) techniques. Inspection methods that can be utilized by robotic systems are relevant for this study.

#### 3.1 Visual inspection

Visual inspection is the most common and widespread NDT technique. It is effective and demands little equipment, but requires more competence and experience from executing inspection personnel. Visual inspection can be performed with direct eye contact or with use of mirrors, cameras and other physical aids.

Visual inspection is an inexpensive method for detecting equipment flaws and defects. A trained technician is likely to detect improper structural installations, certain types of impending structural failure, welding flaws, corrosion development, and cracks.

## 3.2 Infrared Thermography

Infrared thermography can detect heat patterns in the infrared wave-length spectrum that are not visible to the unaided eye. These heat patterns can help identify deteriorating components before they fail.

Infrared thermography is the science of detecting infrared energy emitted from an object, converting it to apparent temperature, and displaying the result as an infrared image. Literally, infrared thermography means “beyond red” (infrared) “temperature picture” (thermography).

Infrared thermography can be carried out using two different approaches, active and passive infrared thermography [10, 11]: In Active Infrared Thermography, another source of thermal stimulation is employed to heat or cool the test object. This technique employs an external source to add extra energy to the study object, generating internal heat-flow that increases the temperature.

Passive Infrared Thermography does not need an external source of heat. The infrared radiation emitted by the object already is collected instead. That is why passive testing is widely popular in in situ NDT of machines and their elements during work or immediately after, when the disproportionate temperature distribution on their surface may be indicative of defects.

With an infrared camera it is possible to capture thermal images without making direct contact with equipment. That means thermal information from operating equipment can be captured at a safe distance and have a better chance of seeing temperature anomalies under normal operating conditions. The non-contact nature of infrared thermography makes it ideal for a wide range of applications where components are moving, very hot, dangerous to contact, difficult to reach, impossible to shut off, or could be contaminated or damaged through contact.

Applications such as petroleum and chemical processing, or cement, plastic or steel manufacturing that involve extreme temperatures and potentially hazardous conditions can all benefit from the level of detail provided by high resolution infrared images which can be captured from a safe distance.

### **3.3 Ultrasonic Testing**

Ultrasonic testing (UT) is a family of NDT techniques based on the propagation of ultrasonic waves in the object or material tested. In most common UT applications, very short ultrasonic pulse-waves are transmitted into materials to detect internal flaws or to characterize materials. A common example is ultrasonic thickness measurement, which tests the thickness of the test object, for example, to monitor pipework corrosion.

All operating mechanical equipment, electrical emissions and most leakage problems produce a broad range of sound. The high frequency ultrasonic components of these sounds are extremely short wave in nature. A short wave signal tends to be fairly directional and localized. It is therefore easy to separate these signals from background plant noises and to detect their exact location. In addition, as subtle changes begin to occur in mechanical equipment, the subtle, directional nature of ultrasound allows these potential warning signals to be detected early, before actual failure. This makes airborne ultrasound very effective.

Ultrasound inspection offers a unique position for condition monitoring as both a standalone inspection technology and as an effective screening tool that can speed up the inspection process and help inspectors determine effective follow-up actions for mechanical, electrical and leak applications.

### **3.4 Radiography**

Radiographic methods utilize X-ray or gamma rays (electromagnetic radiation) to examine the internal structure and integrity of the equipment. Because these waves have short wave lengths, they can penetrate and travel through structural materials such as steel and metallic alloys.

In the oil and gas industry, this NDT method is useful for inspecting welds on pipelines and pressure vessels. It is also useful for inspecting non-metallic materials such as concrete and ceramics. Operating this type of NDT requires conformance to safety regulations.

Typically, radiography uses gamma radiation emitting isotopes. This upsets nucleonic level control instrumentation on pressure vessels and equipment, causing “trips” that result in costly unplanned plant shutdowns and associated process safety risks.

This year, some further development on this field was presented by Oceaneering: The Trip Avoidance X-ray Inspection (TAXI<sup>TM</sup>) system [12]. From Oceaneering’s product description:

*“The TAXI solution enables Oceaneering’s technicians to digitally radiograph pressure piping and infrastructure associated on, or around, equipment fitted with nucleonic detectors. The work can be carried out while the plant is in-service, using a specialized system that delivers pulsed X-rays.”*

*“Our TAXI<sup>TM</sup> solution is suitable for detecting and monitoring corrosion under insulation (CUI), a major issue attributed to around 60 percent of the North Sea’s piping failures. CUI is difficult to detect and measure, and removing insulation to inspect for signs of corrosion can be costly, time consuming and sometimes unnecessary.”*

### **3.5 Acoustic emissions**

This method detects the presence of rarefaction waves produced by leaks in pipelines. When a fluid leak occurs, negative pressure waves propagate in both directions within the pipeline. Detection of these acoustic waves helps identify leakage in pipelines.

Acoustic Emission Testing (AET) is an effective NDT method which is widely used throughout the petrochemical industry. It plays an important role in inspection of atmospheric storage tank floor corrosion, oil and gas pipeline leakage and pressure vessel cracking, having important significance in ensuring the security [13].

## 4 Robotic Solutions

An important development in robotics is the recognition that robots must be able to work in the real world, as opposed to the ideal, clean and organized laboratory environment. Robots must be able to use and operate within the existing infrastructure such as narrow manways, steep staircases, cage ladders, dirty and slippery surfaces and doors. They must be able to handle the presence of unexpected obstacles, withstand inclement weather and sometimes certified to work in a potential explosive atmosphere.

### 4.1 Autonomy

A second important and on-going development is autonomy. Autonomy means a system that decides and performs actions motivated by some intended objectives, and those actions are justifiable by sound reasoning with respect to these objectives. Autonomy differs from automation as it is defined as a system that does exactly what it is programmed to do, without choice or possibility to act in any different way. A robotic system is a machine capable of carrying out complex series of actions automatically.

Systems are becoming increasingly capable of autonomously executing tasks ranging from simple, basic tasks up to complex, fully autonomous navigation and problem solving. In some cases an autonomously operating robot is superior to a remotely, human-operated robot. In other cases, effective autonomy is far from reality.

Autonomy is in general not a binary property, a robot is not either autonomous or not. Instead, it is more appropriate to talk about levels of autonomy. As the engineering definition of autonomy depends on the specific application, so does the definition of levels of autonomy. Most often, an autonomous robot is a system within a larger and more complex system. Consequently the level of autonomy must be carefully selected for any given application.

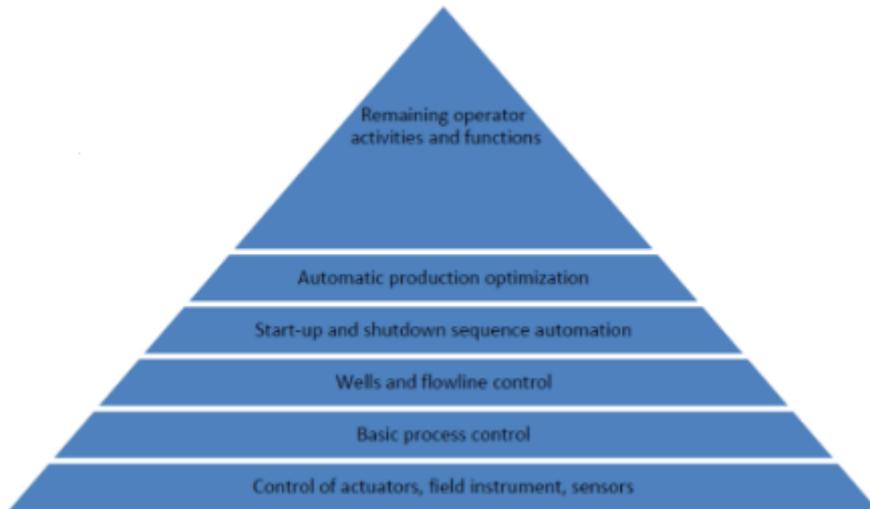


Figure 1: Hierarchy view of main functions in a production platform [14]

All industrial applications of autonomous robotics will not remove the operator from the operation. Aspects to consider with Human-Robot interaction (HRI) are nature of information, comprehensibility, structure of the task and the team and learning and training of people and robot. It is important to consider

Fully autonomous robots designed to perform a single task in a fixed, well-modelled environment will be different than a fully autonomous robot designed to perform different tasks in a diversity of environments, with a range of interactions.

LOA	Name	HRI level	Description
1	The robot is <b>human operated</b>	Teleoperation	Full manual control, the robot visualize information but offers no assistance.
2	The robot is <b>human assistance</b>	Mediated teleoperation	Manual control with robot assistance, the robot visualizes processed information to support decisions.
3	The robot is <b>human delegated</b>	Supervisory control (function level)	Basic form of supervisory control, the operator activates functions that are executed by the robot. The robot process information and provides list of options.
4	The robot is <b>human supervised</b>	Supervisory control (task level)	The operator is in the loop, but the robot executes the tasks. The robot provides necessary information for performance assessment, and option to veto
5	The robot and the human share <b>mixed-initiative</b>	Collaborative control	The operator does not need to be in the loop all the time. The robot executes the task and informs only if requested to.
6	The robot has <b>full autonomy</b>	Peer-to-peer collaboration	The operator does not need to be in the loop. The robot executes the task.

Figure 2: Levels of autonomy in an industry perspective [14]

## 4.2 Advances in robotics

Crawlers for online tank floor inspection are currently available. Inspection methods implemented include visual inspection and UT for measuring remaining wall thickness. Some crawlers are able to cope with limited deposit. Some robots are capable of performing a scan autonomously. The first crawlers capable of navigating a processing plant have been introduced, 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 [15].

Drones are being used for tasks such as flare tip inspection, recording thermographic images and tank roof inspection.

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. Especially subsea, where i.e. the Eelume concept have showed promise, being piloted at the Åsgard field [16].

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.

Autonomous operation and simultaneous operation with other robots and human operators are in various degrees of development. So far robotic inspection 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.

### **4.3 Technology requirements for robotic solutions**

One of the most important technology goals is keeping equipment online during inspection and maintenance. Developing inspection and supporting services that make full online inspection possible is therefore important.

Improving coverage of i.e. Atmospheric Storage Tanks (AST) floor inspection, including the critical zone and floor plate settlement. Avoiding human entry in AST and other confined spaces is vital. Other applications will be taken offline for inspection but avoiding human entry of the asset would generate significant gains in the domain of the business drivers. Also, coating inspection for tank floors and walls, accuracy of localization and online removal of deposit are required development goals for robotic use.

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 personnel. 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.

The requirement for autonomously moving robots to be capable of safely sharing the work space with people or even interact with them. Also, the ability for autonomous robots to be capable of learning from their experience is important to develop an efficient inspection and maintenance scheme.

Inspection of insulated piping may require, depending on the chosen solution direction, further development of measuring remaining wall thickness through insulation. This needs to include local corrosion, such as pitting, and top-of-line/bottom-line corrosion. Coating inspection under insulation will also be a requirement.

Digitization introduces new vulnerabilities linked to information security, sabotage and data manipulation which entails the need for new requirements til working processes and competence. Implementation of new technology and digital solutions will also be dependent on the quality of user interface and their contents in form of data, information and models.

Better understanding of technical condition and data has been driven by better presentation and interface for sharing of data rather than analysis models and predictive maintenance. DNV GL's [17] experience is that maintenance on the Norwegian Continental Shelf (NCS) largely is run by set calendar-based intervals and that the analysis process is barely used in regards of maintenance optimization.

Localisation and navigation are important aspects, for which recent developments have become available for practical applications in the product. Accuracy is an important issue, as this relates directly to coverage. It is desirable that accuracy improves considerably for most applications.

#### **4.3.1 Limitations for implementation of new digital technology**

Use of data:

- Often will available data not be suited for a desired purpose. Data is generated generally as a bi-product of management systems and monitoring systems and is not necessarily gathered for the desired purpose, i.e. to predict

maintenance need on a certain type of equipment [18].

#### Organization and management

- Digitizing in a company should be rooted in the overall goal and the overall strategy. This should include necessary elements and measures that are required for the company to reach its goals, both short and long term.

#### Verification of models

- Models that are used needs to deliver results according to expectations and conditions set. To confirm this, it is possible to verify the development and set requirements for documentation that could demonstrate the model.
- For data driven models it is important to document that the training data are representative for the operational conditions where the models is to be used. It is important to avoid that the model produce results that are adapted to the training data yielding better test results than in reality, this is called over-fitting.

#### Data control

- Operators should have clear requirements for data security defined in the control system which sets demands to suppliers and other external companies that deliver digital services [19].

## **4.4 Opportunities for robotics in inspection and maintenance**

The best opportunities for robotics in inspection and maintenance can be found where use of robotics significantly increases economic output through reduction and/or prevention of downtime of the assets, as system downtime is by far the most dominant factor in cost associated with inspection.

Robots can take over hazardous tasks, such as firefighting and working at height as well as confined spaces. Human entry of confined spaces for inspection is responsible for up to 80 % of asset downtime due to preparation requirements. Robots

can execute tasks at height or other locations that are difficult to reach, 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.

Robots can replace human operators on remote and offshore sites, eliminating the high costs involved with permanently staffing and accommodating crew on such sites and with transporting crew to and from such sites.

Use of robots improves asset integrity significantly through enabling more frequent inspections. This may enable close monitoring of the 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.

Robotizing methods for the detection of humidity in the insulation, for example, using thermographic images or neutron backscatter is a possibility.

## **4.5 Data processing**

Robotized 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, but may also require automatic trend calculations and raising of alarms and warnings.

ISO 13374-1 [20] states that relevant data processing and analysis procedures are required to interpret the data received from condition monitoring activities. A synergistic combination of technologies should establish the cause and severity of possible faults and provide the justification for operations and maintenance in a pro-active manner.

A data processing and information flow of the type shown in figure 3 is recommended either on a manual or automatic basis, in order to implement condition monitoring successfully.

Machine condition assessment can be broken into six distinct, layered processing blocks. The first three blocks are technology-specific. The last three combine monitoring technologies in order to assess the current health of the system, predict failures and provide recommended action steps.

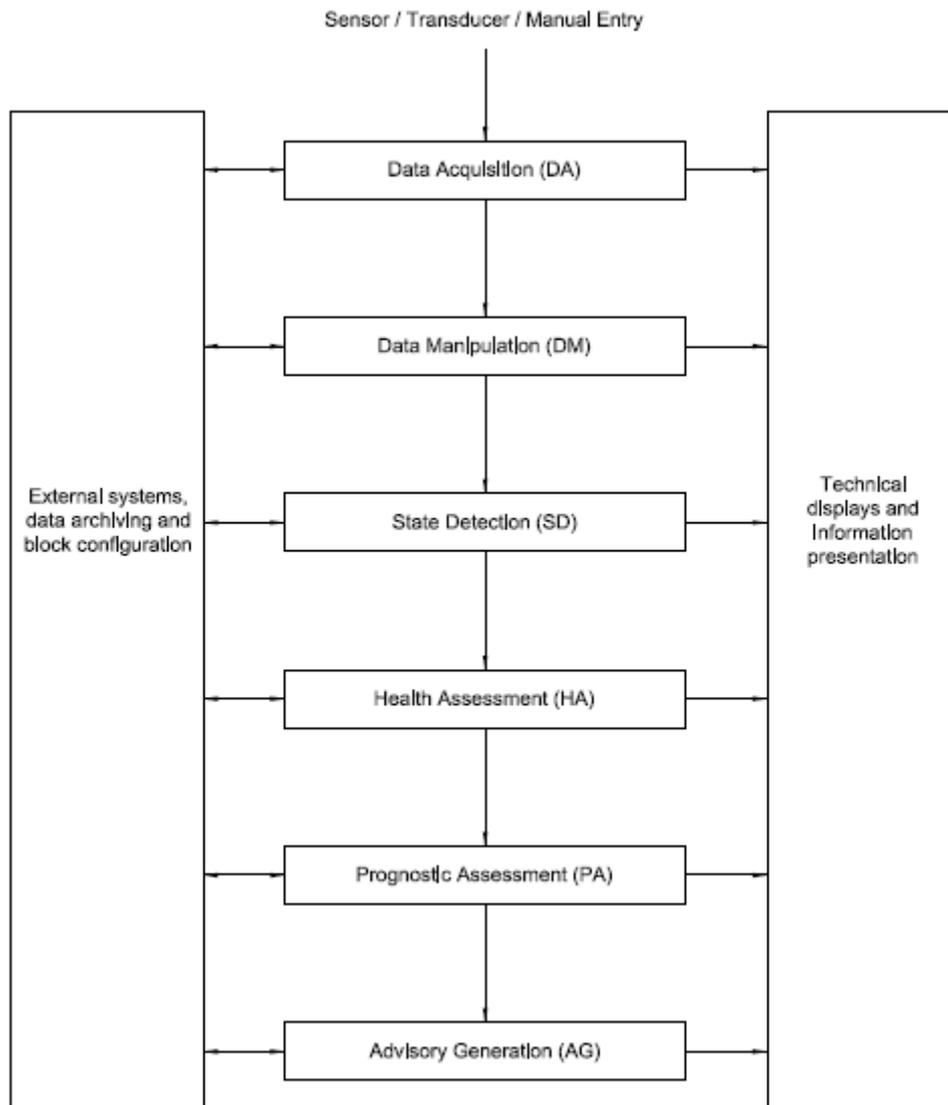


Figure 3: Data processing and information flow blocks necessary for condition monitoring according to ISO 13374-1 [20].

Data Acquisition block:

- Converts an output from the transducer to a digital parameter representing a physical quantity and related information.

Data Manipulation block:

- Performs signal analysis, computes meaningful descriptors, and derives virtual sensor readings from the raw measurements.

State Detection block

- Facilitates the creation and maintenance of normal baseline profiles, searches for abnormalities whenever new data are acquired, and determines in which abnormality zone, if any, the data belong.

Health Assessment block

- Diagnoses any faults and rates the current health of the equipment or process, considering all state information.

Prognostic Assessment block:

- Determines future health states and failure modes based on the current health assessment and projected usage loads on the equipment and/or process, as well as remaining useful life predictions.

Advisory Generation block

- Provides actionable information regarding maintenance or operational changes required to optimize the life of the process and/or equipment.

A complete digitalization is achieved when it is possible to combine available information with data, which through analysis and models decides degree of follow-up. The degree of digitalization will increase with the degree of interaction between systems. automatizing of processes and development of autonomous systems that self-diagnose and plan maintenance.

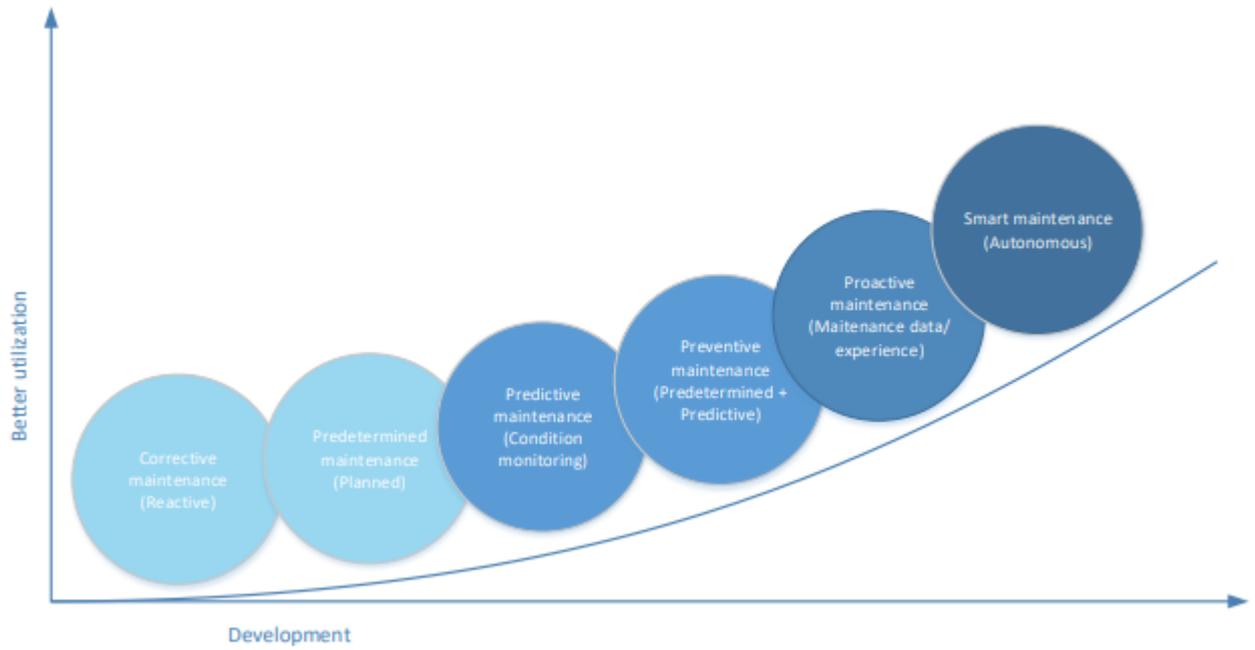


Figure 4: An illustration of levels and degree of utilization of data through digitalized maintenance [17]

## 4.6 Standard requirements

There are no specific government standard for use of robotic equipment on unmanned facilities. However, there are many standards for other equipment and procedures that can be used as guidelines for implementation. ISO 18436 [22] defines the following standardized measuring techniques:

- Vibration
- Oil analysis
- Acoustics
- Thermography
- Ultrasound

These are techniques that could be fitted on an autonomous robot on an unmanned platform. Combining this with i.e. standard requirements from the subsea industry could make a foundation for a new standard for robotics topside. It is also possible

to take advantage of existing standards on cyber security and safety requirements.

## **4.7 Swarm Robotics**

Small robots on their own have little power, but together are able to execute involving and complex tasks.

The field of swarm robotics concerns the coordination of multi-robot systems composed by a large number of robots, where the collective behavior emerges from simple local interaction among teammates and between the robots and the environment. This local interaction may be accomplished using direct communications (e.g., radio frequency, infrared wireless systems) or indirectly through the environment, by leaving markings that the teammates can recognize [21].

Swarm robotics concepts are inspired by the field of swarm intelligence (SI), which studies the collective behavior of (natural or artificial) self-organizing agents. The fundamental drive for swarm intelligence (SI) comes from the idea that global intelligence, to accomplish global tasks, emerges from local interaction of less intelligent individual units.

## **4.8 Practical case - Taurob Tracker**

To get a first hand practical experience with a real crawler, it was arranged a test run of the Taurob Tracker. The Taurob Tracker system is a reconnaissance robot for emergency personnel. By means of remote control, this robot is able to penetrate areas that are contaminated by harmful substances (gases, radiation, liquids) and are therefore inaccessible to personnel or dangerous and can therefore only be accessed with considerable risk and effort.

The taurob tracker consists of the robot platform and pivoting arm. Figure 5 illustrates the robot and its components. The crawler track is dynamic by design. This means that you can move the front guide wheels up and down. This way it is possible to overcome higher obstacles and align the centre of gravity of the robot with the terrain.

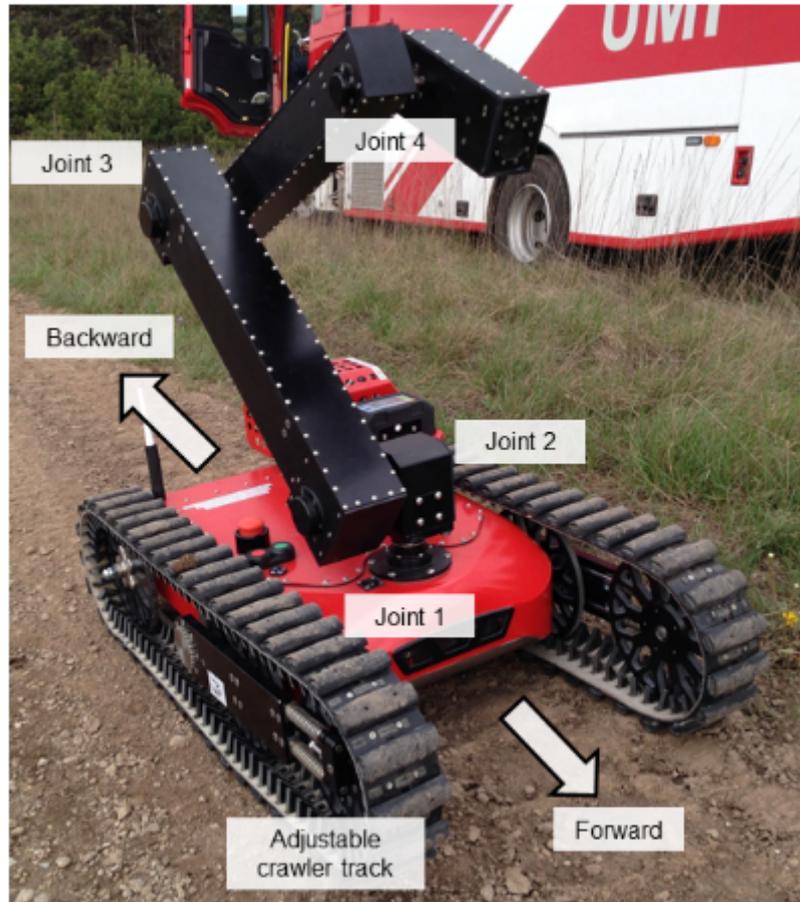
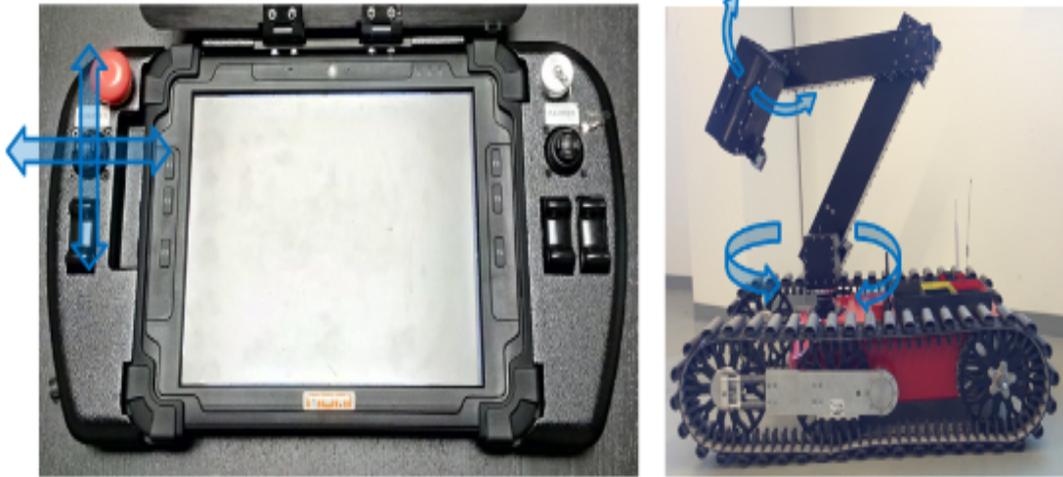


Figure 5: The Taurob Tracker

The arm offers 4 degrees of freedom: Complete rotation of the entire arm (joint1), tilting of the first element from 0-180° (joint2), pivoting of the second element from 0-270° (joint3) and pivoting of the camera from -140 - 150° (joint4).

The system is equipped with multiple cameras, in order to transfer live images: One camera at the front and rear in the housing respectively, as well as various optional cameras on the arm. LED headlamps are also located in the vicinity of each of the cameras, ensuring good illumination in darkness. At the end of the arm is an optional gripper or a retainer for measuring devices. An infra-red camera is optionally integrated in or on the last element of the arm.

The drive operation of the robot can be controlled with the left stick, on the tablet PC. In order to move the robot forwards push the stick forwards, and to reverse the robot push it backwards. The deflection of the stick determines the speed of the robot.



(a)



(b)

Figure 6: Control mechanisms of the Taurob Tracker. On the left: The control pad.

In order to avoid complex positioning of the arm, pre-set arm positions exist. This include the:

- Look position: This position offers a good initial position from which to view things in front of the robot or perform manipulations with the optional gripper
- Transport position: This pre-set position folds the robot down completely

for transportation

- Drive position: The robot has diverse drive modes that enable it to cope with varying terrain and stairs more easily and above all more safely. As previously mentioned, the arm has a significant influence on the centre of gravity of the complete system. The precise arm position must therefore be taken in to consideration during all driving situations.

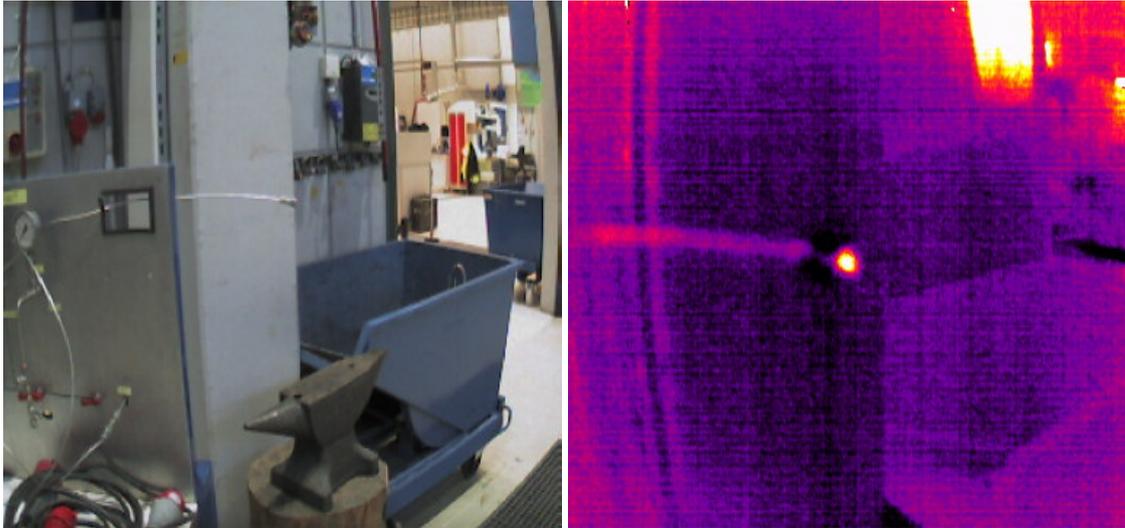


(a) The Taurob Tracker going up stairs      (b) The Taurob Tracker going down stairs

Figure 7: The Taurob Tracker in drive mode, going up and down stairs

#### 4.9 Practical case - Thermography camera experiment

This case was a possibility analysis for an IR camera that could be put on an autonomous robot doing inspections on an unmanned platform. The camera was provided by Equinor. The first test was a comparison when using the IR camera on a nozzle emitting  $N_2$  gas, as can be seen in figure 8.



(a) Regular photo of a nozzle emitting  $N_2$  gas (b) Thermography photo of the same nozzle emitting  $N_2$  gas

Figure 8: Comparison of images finding heat/cold spots when using the thermography camera

The next test was using the thermography setting on the camera on a multi phase compressor. The compressor was located at the Department of Energy and Process Engineering at NTNU. The compressor was run for ca. 20 minutes, to get a significant rise in temperature, yellow color was set to appear at  $30\text{ }^\circ\text{C}$ , depicted in figure 10.

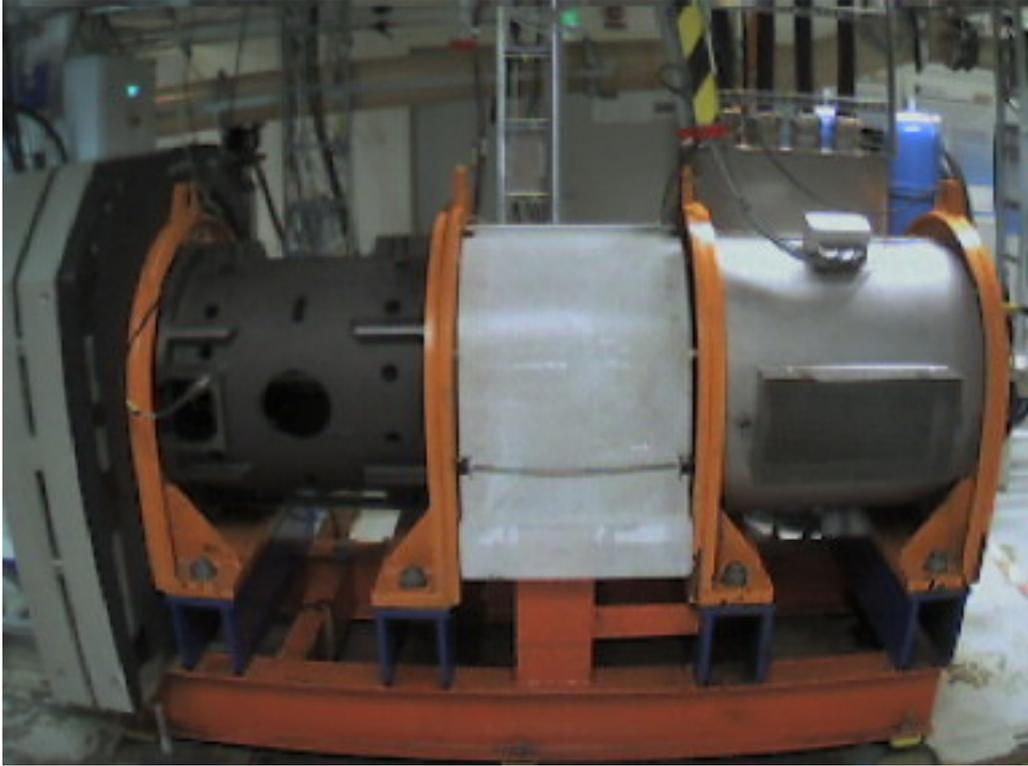


Figure 9: The compressor used in this experiment

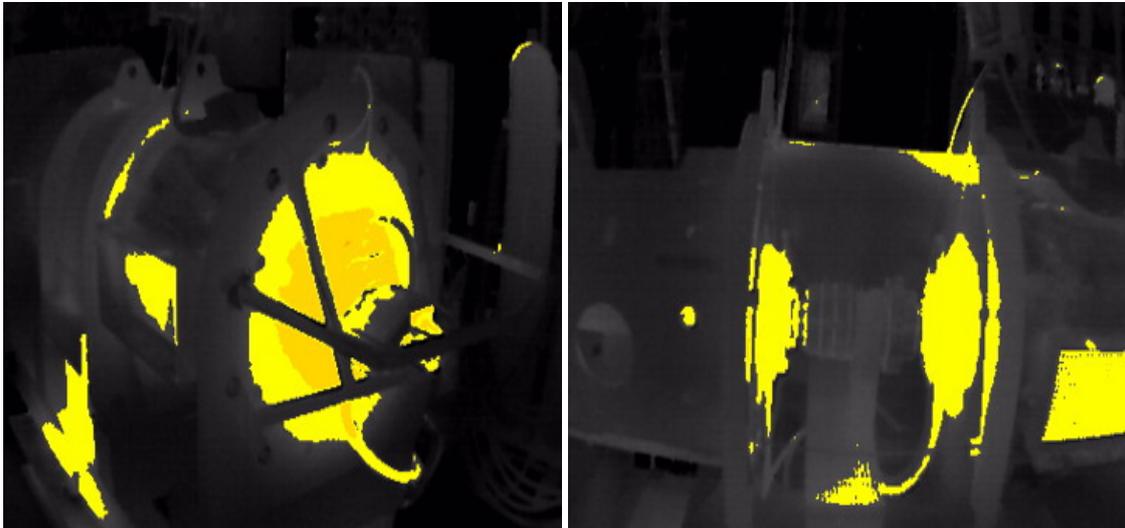


Figure 10: Pictures taken of the compressor with a thermography camera

This shows that it is possible to detect anomalies in temperature on various equipment. This technology can be used to detect i.e. a gas leakage, overheated equipment and monitoring EX equipment on an unmanned platform.

## **5 Discussion**

In this section, answers to the main questions asked in the interviews will be discussed as well as key findings in the previous segments.

### **5.1 Maintenance-heavy equipment on today's facilities**

To assess maintenance needs it is important to know where the asset is in its life cycle. With an older asset it is usually surface treatment of Electrical equipment in hazardous areas (EX). One of the interview subjects said that half of the maintenance hours goes to scheduled maintenance, almost all of this on EX control, testing of safety functions and certifications. Other systems are auxiliary systems such as water supply and diesel systems. Also, rotating equipment and degradation of pumps and valves are a heavy maintenance issue, as well as fire & gas systems.

Some of these systems are not as prioritized in the startup as there is more focus on production and power production. Often, there might be used lower material quality since it is possible with simpler specifications. Also, many of these systems will be redundant when starting an unmanned facility, i.e. auxiliary systems, but protection of EX equipment will still be necessary as the risk of environmental and economic loss are still as high.

### **5.2 Condition monitoring as a tool**

As a surveillance function, condition maintenance is a part of the information system that contains all information in one place. This makes an effective use of attention and resources in an organisation.

Condition monitoring is already used in some forms. Main sensors could be high resolution visual cameras or infrared camera to check heat spots on equipment. Also microphones or acoustic sensors to monitor the noise from equipment, especially for rotating equipment. Putting this on a robot will introduce a lot of

flexibility.

An advantage with a complete condition monitoring system is that it can verify that the quality of new or repaired equipment is in accordance with specifications. After larger maintenance project, this could stop that machines in bad conditions are set back into full operation. As a result, many suppliers deliver reference values for comparison. This needs to be a norm when dealing with condition monitoring.

For successful condition monitoring, solutions is required to be reliable, be able to detect degradation before failure and should not introduce new sources of errors. It is also important with high accuracy in measurements and automatic data collection. When retrieving data it can be advantageous with high flexibility, meaning all measurement data goes into the same system.

With today's technology, these requirements should already be possible to implement with good instrumentation. When implementing this technology on a robot on unmanned facilities, automatic analysis of retrieved data is useful to add on. When interacting with maintenance personnel, there should be a user friendly interface and software, presenting information in an unambiguous and straightforward manner.

Combining condition based models might be the best approach for implementation on robots. In example, putting physical laws as constraints on a data driven CBM could yield good results, lowering the need of maintenance.

When asked about the use of condition monitoring in the interviews, it was brought up that there is not enough trust in new condition monitoring technologies. Even though it exist sensors with continuous self diagnostics, it is still checked every year. Condition monitoring on unmanned facilities might force operators to trust more in technology, including self diagnosis in the maintenance scheme. If this is not desirable, robotics could take responsibility for diagnostics check when the platform is unmanned.

### 5.2.1 Digitalization of maintenance

If the focus is to optimize maintenance to achieve highest possible availability on equipment, for the lowest possible cost, the type of maintenance should be adapted to the criticality of function and failure mode.

A level where one could say that maintenance is greatly digitalized is when it is possible to connect data across systems and share data with other actors and industries. This information needs to be standardized for this to have an impact. Data and information can be used in analysis to decide time and scope of maintenance, as well as continuously improving the program. Access to huge amount of data will help significantly. The predictive maintenance will use all CBM-models, but the data driven model will be dominating. Equipment should be integrated with systems that can predict condition and decide the next move. A certain degree of remote maintenance might be applicable on this level.

To get more digitalized maintenance, further studies in the following areas can be helpful:

- Studies on how data control, data security, infrastructure and network could affect governmental supervision.
- Studies on facilitating for future competence needs. This could include evaluation around if today's regulations is sufficient to meet the future development. The study could be used to establish guidelines for future competence building in the industry.
- Establishing a common digital platform for maintenance and technical condition. The platform can be developed in collaboration with operators with focus on safety and integrity and the operators can learn by sharing information.

## 5.3 Inspection of unmanned facilities

Most, if not all, inspection methods lends 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 of the surface to be inspected, either because the asset is filled with non-transparent product, or the asset has not been cleaned prior to 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. Hence, traditional visual inspection may need to be replaced by methods such as UT, electromagnetic or other techniques. Hardware and procedures will often need adaptation to robotic deployment. Applications would include corrosion and crack research.

While infrared is typically used to locate electrical problems, there are “sound” events that could go undetected when relying on infrared thermography alone. Enclosed cabinets can be scanned, transformers can be probed and corona can be detected in high voltage equipment. Sound samples can be recorded for analysis and spectral or time series views can be placed in reports.

Ultrasound condition monitoring provides many opportunities to improve asset availability, keep production on schedule and save energy. Applications for mechanical analysis, electrical inspection and leak detection cover just about all plant equipment.

### 5.3.1 Opportunities for robotic inspection and maintenance

The interview subjects had many ideas on which tasks that could be taken over by robots on an unmanned facility. Mainly, surface monitoring and NDT methods without touching the surface are viable.

An exciting opportunity is that the robot can connect with software in the control system, and build 3D-models that can report about anomalies that needs attention

or action. This will be helpful for inspectors.

Implementing robotic inspection will take time. Initially, it can be used as a helping hand for maintenance personnel, inspecting confined spaces - tanks and pressure vessels, where you don't want people inside. Coating of surfaces on hard to reach areas which requires climbing can be streamlined by use of robots. Using the robot as an additional tool will make the inspection team work faster, safer and cheaper. Further development will let the robot do visual inspection, and use IR camera and ultrasound methods. Further down the line it can be able to make small modifications or correctional tasks.

Using a robot as first responder on emergencies will be useful. It takes time to mobilize ships out if there is a failure. It is possible to put in redundancy, but this will be costly. It would also be very useful to, if there is a shutdown, be able to send out a robot with a camera to do the first inspection and localize a leakage or similar.

Making fully autonomous inspection is not likely with existing platforms. These are made for facilitating humans and will be costly to change drastically. When building an unmanned platform, it will be made as simple as possible, no helicopter decks, no accommodation and all equipment facilitating humans will be gone.

Robotic inspection is more likely than maintenance to be implemented. This is because of no standardization of equipment that robots will interact with, i.e. valve-wheels etc. Pushing suppliers to make standardized equipment topside, like it is subsea, will be necessary.

One interview subject said we might have to think in new directions, not just let robots take over human tasks, they might be too complex and too many. Everything needs to be done in design first, and then what is left is for the robots, i.e. small interventions, turning valves and visual inspections.

From the experiments, it should be possible, and very likely that a version of IR cameras will be implemented on inspection and maintenance robots topside. The camera will be able to detect i.e. a gas leak better than humans, and it's recommended that this is implemented as soon as possible to assist mounted gas

sensors. Other sensors that could be put on a crawler such the Taurob could be microphones, lasers, ultrasonic sensors or similar NDT methods.

### **Swarm robotics**

One major drawback of swarm robotics is that the robot collectives controlled using its principles of simplicity and local interaction are usually inefficient in carrying out a given task, trading efficiency for robustness. Typical swarm robotics approaches often under-exploit the potentially high level of cognition and networking available to the individual robots.

An interview object said there is a lot of technical challenges with this. Swarm robotics need a very precise navigation system. A higher demand on the technical side tends to make the robot considerably more expensive, which eats up the margin of the desirable solution. On paper it is a very exciting and maybe feasible. Making a product right now is not economically viable.

## **5.4 Technical and standard requirements**

There is no standard for robotics topside in the oil and gas industry. Standards exists for automation, control and tele-com, safety, cyber security and other disciplines. There is also a standard for ROV's subsea. Operators needs to get collectively together to make an operator spec. This will probably be a result from experience with the technology combined with using other relatable standards.

The design phase could remove a lot of maintenance. Right now it is designed for people. It might not be possible to design your way out of everything, that's where robots come in. To facilitate autonomous robotics, a subsea mindset is needed. The structures need to be robust, have high resistance and be as simplistic as possible. This is why it is easier to envision with new facilities, rather than changing the old.

If an unmanned platform is designed to implement robotic inspection and maintenance from day 1, then autonomous inspection is possible and often maintenance might not be facilitated at all. It boils down to creating the correct maintenance

scheme, although accessibility in design will create a higher CAPEX. To ease the CAPEX, maintenance tasks need to be concrete and fitted to the type of robotic solution chosen.

## 5.5 HSE

Less exposure of personnel will generally have a positive effect on personnel risk as humans are removed from dangerous areas. At the same time human errors are removed, thus dropping the probability of humans introducing perilous situations. A Sysla article [23] writes that Equinor's remotely operated Valemon field has not had downtime in a period of 1 year of operations. Simultaneously, the article describes that troubleshooting takes more time as a result of remote control. Introducing autonomous robots with automatic inspection intervals could reduce time for troubleshooting, making the operation safer in the process.

Because of increased response time on remotely controlled or unmanned platforms, there is a higher risk related to emissions and major accidents. More monitoring, i.e. from sensor, use of IR camera and video surveillance, and an effective emergency preparedness that includes standby boats and support from nearby fields, could reduce this risk considerably.

Digitalization of requirements is a relative new field, and the effect on risk for personnel safety, major accidents and emission is hard to assess. Given that digitalization of requirements makes it easier to verify that requirements are met, it could be likely that this leads to more compliance of safety related requirements, reducing risk.

The most important point is that implementation of inspection robots needs to be safe. There needs to be requirements for not causing a leakage, fire or damage to inspectors and assets.

## 5.6 Autonomous robotics

Autonomy implementation in the industry is driven by the value potential to the business. It is important to consider its role in the value chain as well as strategic goals such as efficiency, safety and security and data value management.

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 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. 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.

Full autonomy is difficult. The robot may encounter a situation it does not recognize. The execution of the task must then be interrupted, leaving the robot in a safe state and situation, and an operator must be alarmed to solve the situation, for instance in remote control mode. The situation may change during autonomous execution of the task. The execution of the task is then interrupted by an operator and a new task may be initiated. Execution of the task may need planned intervention by an operator. A crack being monitored may have grown at an unexpectedly high rate, requiring a human decision concerning the next action, such as additional inspection by the same robot.

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. It is essential to select the correct level of autonomy for the application.

## 5.7 Economical impact

The oil and gas industry is a capital-intensive industry, great financial investments are needed in order to make production possible. This holds for the initial building costs, as well as the costs for inspection and maintenance. As a result, costs per production hour are very high.

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 of the applications, much of the off-line time is caused by preparation for inspection and maintenance. This includes preparation for human entry of confined spaces, such as tanks and pressure vessels, scaffolding and removal or renewal of insulation. Other cost-intensive aspects are the transport of a crew to a remote site and the number of people on board for an offshore installation.

There is much more goodwill in investing in robotics from the management, since they can see the specific opportunities in robotics, especially in regards to design directed against green fields.

Economically, this creates a trade-off between designing for robotic inspection and maintenance in the early stages of design versus performing correctional or calendar based maintenance without condition monitoring. Designing for robotics will have a larger cost, but as maintenance is a large economic post in a budget, this could be profitable in the long run. As one of the interviewed subjects put it:

*“The pot of gold under the rainbow is to be able to get fully automated platforms that doesn’t need maintenance attention every third month, the management realize this.”*

## 6 Conclusion

Unmanned wellhead platforms are in use today in the offshore industry, while more complex installations with requirements for processing are developed as permanent manned installations. Some technological developments could, however, contribute to possible future larger unmanned installations with processing. Better and cheaper sensor technology, improved access to data, improvement of software and tools and increased processing capacity will in combination with simplified design and robust components with redundancy be used to develop large unmanned offshore facilities.

Drivers in the petroleum industry are safety improvement; human safety as well as environmental safety. Cost avoidance and reduction. Environmental performance improvement; reduce production of waste, prevent leakage and catastrophic events. It is also desirable to increase operational efficiency and cost reduction/avoidance. Defining maintenance-heavy equipment and introducing condition monitoring are important factors for improvement in these fields.

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 risk 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 to events. Parallel to this, a line of robots might be developed for tasks like pressing buttons, operating valves, firefighting and small, possibly temporary, repairs.

Inspection and maintenance tasks possible to be taken over by robotics are:

- NDT methods such as visual inspection, ultrasound testing, radiography etc.
- Gas & fire detection.
- Surface monitoring.

- Coating and maintenance in confined spaces or at high altitudes which suggest a health risk for humans.
- Build 3D-models with reporting to inspectors.

There is a need for standardized equipment topside, ensuring this requires a lot of thought in the concept phase. It is vital to have an unmanned platform approach from day 1. Monitoring is not the biggest issue when implementing autonomous robotics, performing maintenance is the main issue. It is important to have a subsea mindset with a design that is as simplified as possible. Module based design could make it easier to switch components and equipment, both on the facility and on the robotics itself.

From an economic standpoint, designing for robotic inspection and maintenance will have a larger cost, but as maintenance is a large economic post in a budget, this could be profitable in the long run.

## 6.1 Further work

Possibilities for further work include:

- Studies into how to make a standard for use of robotics on an unmanned installation.
- Studies on design for facilitating autonomous robotic inspection. I.e. accessibility and standardized equipment.
- Studies into which EX equipment will be necessary on an unmanned platform, as well as EX proofing of robots and EX certification.
- Work on robotics concepts. Which concepts are viable for a standardized inspection method? Crawlers vs drones vs rail attached vs swarm robotics.
- Studies on fire & gas detection with different cameras vs. sensor equipment.
- Implementing a subsea mindset for topside unmanned facilities.

- Ensuring sufficient cyber security with the implementation of wireless communication between robots and control system.

## References

- [1] L. Pintelon and A. Parodi-Herz, Maintenance: An evolutionary perspective. Springer, 2008.
- [2] B. K. N. Rao, Handbook of Condition Monitoring, 1st edition. Oxford: Elsevier Advanced Technology, 1996.
- [3] P. J. Tavner, J. Penman, L. Ran, and H. Sedding, Condition monitoring of rotating electrical machines. The Institution of Engineering and Technology., 2008.
- [4] A. Wilson, Asset Maintenance Management: A Guide to Developing Strategy & Improving Performance. Industrial Press, 2002.
- [5] International electrotechnical vocabulary – Part 192: Dependability, NEK IEC 60050-192:2015
- [6] Vedlikehold – Vedlikeholdsterminologi, NS-EN 13306:2017
- [7] Condition monitoring and diagnostics of machines — Vocabulary, ISO 13372:2012
- [8] Condition monitoring and diagnostics of machines — General guidelines, ISO 17359:2018
- [9] R. Steine, Assessment of the potential for condition monitoring at Jøssang Power Plant. Universitetet i Stavanger: Teknisk-Naturvitenskapelig fakultet, 2016.
- [10] F. P. G. Marquez, M. Papaelias, and A. Karyotakis, Non-Destructive Testing and Condition Monitoring Techniques for Renewable Energy Industrial Assets, 1st ed. Butterworth-Heinemann, 2019.
- [11] A. Rudawska, Surface Treatment in Bonding Technology, 1st ed. Academic Press, 2019.

- [12] Oceaneering.com, Oceaneering's TAXI™ Digital Radiography Solution to Provide Significant Cost Savings, 2019, <https://www.oceaneering.com/oceaneering-develops-trip-avoidance-xray-inspection-taxi-system/>
- [13] Chen JF, Bi HS, Wang Q, Wang AQ, Sheng H, Rong HX. The Application of Acoustic Emission Technology in Oil and Gas Storage and Transportation Equipment. Advanced Materials Research, 2013
- [14] F. Scibilia, TTK23 - Introduction to Autonomous Robotics Systems for Industry 4.0 lecture 5, 2019
- [15] SPRINT Robotics, Sprint Robotics Strategic Roadmap, <https://www.sprintrobotics.org/wp-content/uploads/SPRINT-Roadmap-February-2018-V2.0.pdf>, Report nr 16012 rev 2.0, 2018
- [16] Equinor.com, <https://www.equinor.com/no/how-and-why/etv-news/eelume-to-be-piloted-at-aasgard.html>
- [17] Petroleumstilsynet, Digitalisering i vedlikeholdsstyringen og bruken i analysearbeidet, Rapportnr.: 2018-1250, Rev. 1, Dokumentnr.: 244523, 2019
- [18] Data science and machine learning in an industrial context, DNV GL, 2018
- [19] NEK IEC TS 62443-2-1, Industrial communication networks - Network and system security, 2010
- [20] ISO 13374-1, Condition monitoring and diagnostics of machines — Data processing, communication and presentation — Part 1: General guidelines, 2003
- [21] D. Milutinović and P. Lima, "Biological cell inspired stochastic models and control," *Microbiorobotics*, pp. 145–161, 2012, doi: 10.1016/B978-1-4557-7891-1.00006-2.
- [22] ISO 18436-2 Condition monitoring and diagnostics of machines — Requirements for qualification and assessment of personnel — Part 2: Vibration condition monitoring and diagnostics, 2014

[23] Sysla.no, M.M. Bringslid, <https://sysla.no/offshore/fjernstyring-fungerer-bedre-enn-noen-hadde-trodd/>, 2018

## Appendix A - Main outtakes from interviews

*“Which systems do you think are the biggest challenges concerning maintenance hours and resources today?”*

- It is important to know where the asset is in its life cycle. If the asset is older, then surface treatment of EX equipment is the main issue. If it is newer, usually error corrections on the equipment installed itself is the main issue.
- There could be an update of an existing product that causes a failure mode, where the failure cause might be old infrastructure.
- Degradation in valves and barriers is a problem
- Auxiliary systems such as drinking water, lavatories, instrument air and diesel systems is not as prioritized in the startup as there is more focus on production and power production. Often, there might be used lower material quality since it is possible with simpler specifications.
- Many systems are a problem, but typically rotating equipment and pumps and valves contribute a lot to maintenance jobs. Often because they don't meet the requirements set.
- Inspection on outdoor structures, especially with drones
- Gas turbines and power supply.
- Fire & gas and evacuation systems.
- PSV's because of need for re-calibration and testing
- Half of the hours goes to scheduled maintenance, almost all of this on EX control, testing of safety functions and certifications. Would like to get those hours down, but it's impossible to get away from rules and requirements on this equipment.

*“Which technologies are chosen for condition monitoring and inspection of remote facilities today?”*

- There are already technology for this subsea, but it is not installed. We have looked a lot on detection, but this is still a ”state of art” challenge. Subsea IoT has a growing market, i.e. wireless riser monitoring or autonomous cameras med different functionalities, also subsea wireless communication has to be standardized so that drones can talk to sensors etc. Implementing these practices topside is important for more condition monitoring and autonomy.
- Partial stroke on valves is a system that is spent millions on and rarely gets used. They are installed, but when production starts there is little time, as the focus is on getting systems operational, thereby partial stroke is not satisfyingly tested. Partial stroke then often fails on first test causing a trip in production and flaring, yielding little belief in the system and abandonment of the idea.
- There is not enough trust in new condition monitoring technologies. I.e. there exists gas detection sensors with a small internal gas cell letting the sensor do a self diagnosis each day. Still it is checked every year if it’s working. Self diagnosis is therefore not included in the maintenance scheme. Albeit not exactly a maintenance function, you have two pressure transmitters, one that connect to SIS and one that connects to the control system. To test them they are taken out of operation, instead of comparing them and verifying on the control panel.
- There is a lot of monitoring that goes to the control room, but the impression is that it doesn’t really get analyzed and put in system.
- Drones can get used for inspection, but usually for inspection of hull on ships, not really where it’s hard to get to.
- It is already used in fixed mounted form. Main sensors for robots are high resolution visual cameras, infrared camera to check heat spots on equipment. Also microphones or acoustic sensors to monitor the noise from equipment, especially for rotating equipment. Putting this on a robot will introduce a

lot of flexibility.

- As a surveillance function, condition maintenance is a part of the information system that contains all information in one place. Effective use of attention and resources in a organisation. Surveillance of vibration, valves and electric systems which reports to the same system. Technology behind this is basically instrumentation (pressure, temp, flow, torque).

*“What about Swarm Robotics?”*

- A lot of technical challenges with this. Swarm start to move into robot-robot comm. and cooperation and you need a very precise navigation system. Higher demand on the technical side, which tends to make the robot considerably more expensive, eats up the margin of the solution you want to put in place. On paper very exciting and maybe feasible. Making a product economically its not viable.
- At uni level there is a lot of exciting work. All this is done in lab, built a ”fake” clean and perfect environment. Works in the lab, was also used last Olympics, so it could work in real life. Increasingly more used, requires some type of coordination. Open space in air: can use GPS.

*“What are the technology gaps for achieving more autonomy in inspection and maintenance?”*

- It is important to use the technology that already exists. I.e. technology for condition monitoring for rotating equipment is already out there. Much time goes with developing our own system, but it is time to check what is qualified in the market.
- For new designs it is important to make things as reliable as possible, we need more modules, a more subsea mindset.
- There is a lot of tasks in the design phase that can be changed, mostly for accessibility for the robots, drones can fly, but things need to be facilitated.
- Suppliers need to be challenged to make a standard interface for operation and make inspection targets available for robotic inspection.

- Implementing the existing technology is an issue. There is need to understand the technology - the limitations and the possibilities.
- Access to raw data from suppliers is necessary. If monitoring is outsourced, then the supplier might hold on to their raw data and analysis tools, if condition monitoring and robotic inspection is to progress, then at least available raw data is of a huge importance.
- There need to be requirements for equipment topside to be standardized, for example valves with a robot interface, like subsea valves has for ROV's.
- Robots must be EX proof.
- Better maneuvering system for flying robotics
- The goal should be to be able to make a drone inspect by pushing a button or not even that, it does it autonomously, might not take long to be there.
- Inspection will be easier to implement than maintenance.
- Subsea mindset could be done. Subsea there were no other way than with robots, to risky for humans, but that's not the case for topside. Topside is tougher competition with persons, human is cheaper than the robot.
- A Challenge is EX certification. All equipment on platform where HC is processed. Certification that this equipment will not cause explosions. Techniques for ex equipment does not function well when applied to drones, drones are more heavy, have lesser performance, you loose a lot of the benefits from using a drone. With crawlers the situation is different because of the weight not being a big issue, but still its an important requirement
- There need to be requirements to keep the solution as simple as possible, we want to simplify the maintenance scope, too complex robots requires maintenance itself.
- Concepts are not described fully. On subsea you know, but not topside, that is going to be unmanned. There is no standard for user interface that the supplier is to deliver for remotely operated facilities or by use of robotic

solutions.

- Facilitation for access of robots and robot interfaces. It is necessary to think how everything is to be done without people. There will probably be less interventions, and not large ones. This includes EX and collisions.
- Cyber security will be important since it will be wireless communication and you might be vulnerable for attacks.

“Could a lack of instrumentation be a problem for achieving enough raw data?”

- The biggest issue here is to understand the raw data. Sometimes there is an abundance of raw data, but how the raw data has been affected on its way from the sensor to a digital twin is vital to understand. I.e. timestamps from IO might be different from the timestamp in the control system. All controllers needs to be on the same time.

*“Which manual inspection and monitoring tasks could be done by robots in the future?”*

- Surface monitoring.
- Coating of surfaces on hard to reach areas which requires climbing can be streamlined by use of robots.
- NDT methods, especially Ultrasonic testing
- Inspection of confined spaces - tanks and pressure vessels where you don't want people inside.
- Build 3D-models that can report to inspectors about anomalies that needs attention or action.
- Inspection of gas leakages
- It would be very useful to, if there is a shutdown, be able to send out a robot with a camera to do the first inspection and localize a leakage or similar.
- Might have to think new, not just let robots take over what humans do today, it might be too complex and too many tasks. Everything needs to be done

in design first, and then what is left is for the robots, i.e. small interventions, turning valves and visual inspections.

- Overall visual inspection, checking valves. Inspecting for structure integrity - corrosion, cracks. There is also possible with emergency response (robot as first responder). Inspections of tanks is a big thing, also flare inspection.
- The first step is to help the inspection team, using the robot as an additional tool to make the inspection team work faster, safer and cheaper. Next step is more simplified job until no need for people at all.
- The most part of what we do when we are out on inspection is not really in the scope of inspection. We look at other systems, surface, isolation, gas leakages. the inspection bit you could almost remove today, 90 percent is what we already know is broken and then we check how it has failed. If you know a thing has failed, you don't need to send out a robot to say that, yes it has failed.
- Regular housekeeping to prevent rust and corrosion. Lots of salt in modules and materials will be most demanding.

*“What are the technical/standard requirements for making autonomous inspection possible?”*

- NORSOK has a spec for HART communication towards field instruments. It is an overlaid signal that reveals the health of the instrument. Today you connect with a HART calibrator and retrieve it locally. It is desirable to get this communication into databases, and perhaps use HART comm. for condition monitoring. This requires some hardware installations. Unfortunately there is a requirement that you can't go in and tap HART communication from PSD at this time.
- There is no standard for robotics in the oil and gas industry. It exists for automation, control and tele-com. There is a standard for ROV's subsea.
- Operators needs to get collectively together to make an operator spec. This will probably be a result from experience with the technology, it is difficult

to write a standard with limited experience.

- The design phase could remove a lot of maintenance. Right now it is designed for people. Cannot design your way out of everything, that's where robots come in.
- It is necessary to be concrete on type of tasks, robots can't do everything, it is needed to go into detail; Is there to be inspected with crawlers, or another method, is there to be a combination with locked sensors etc.
- The most important is that it needs to be safe, there needs to be requirements for not causing a leakage or fire.
- There is not a clear standard that can be followed because its very new concept, could apply standards on cyber security and standards on safety.
- From day 1: Autonomous inspection is no problem, maintenance is not facilitated. Monitoring by robots is not far into the future. Accessibility in design will hurt CAPEX.

*“Which level of autonomy do you see reasonable for inspection methods?”*

- Level of autonomy vary from method to method, some with a level of autonomy, some remotely operated. To achieve a high level of autonomy, the technology needs to mature, it is possible to obtain. I.e. Autonomous survey exists. Further autonomy needs to be controlled, and the technology needs to be trusted.
- Want a high level of autonomy, remote control is maybe possible for some inspections, but highest possible level of autonomy. Might get away with automated.
- For certain tasks it will be fully autonomous. Still be an operator in the loop to initiate the task. Normal operation his job will be simple.
- A lot of the challenge to get towards more autonomous solutions is to break with today's technology. It a lot about challenging the requirements from the authorities. Discussions with PSA Norway (Petroleumstilsynet) om what is

good enough will be important.

*“Will robotizing inspection and maintenance lead to more maintenance issues or economic issues? Example: Implementing gas detection on robots.”*

- Applying i.e. a FLIR camera will definitely find many tiny leakages that might not get caught otherwise, but this will of course lead to more maintenance work.
- Applying cameras for inspection is probably to prefer over operators using handheld devices. Because of the operator having to make decisions and evaluate while holding the device.
- Cameras on robots will be an addition to the gas sensors that should be placed anyways.
- A gas detection camera for a robot will be cheap compared to everything that is necessary to organize a robot offshore. Technology qualification is not cheap either, in the big picture
- Replacing gas detection sensors with a gas detector on a moving robot will yield worse detection. You need to invest largely in many robots to be able to do the same job as the sensors do today.
- Should work to not make that happening. Tendency with unmanned platform, simplify, not to complex the scope.
- IR could detect more than humans.

*“Is there a lot of goodwill from the top management for achieving more autonomy?”*

- The top management is much more open now, since they can see the specific opportunities, especially in regards to design directed against green fields.
- The pot of gold under the rainbow is to be able to get fully automated platforms that doesn't need maintenance attention every third month, the management realize this.
- Yes.