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Evaluation of the potential for automation and robot technology, with focus on condition monitoring on static systems for topside offshore facilities.

Abstract

Digitalization has become one of the most important development areas across industries and work processes. We know that this also has high focus in the oil industry today. Therefore, my contribution would be to try to see where the oil and gas industry is today, the trends and what are the potential moving forward.

Automation and use of robot technology has developed very rapidly the last years. Technology trends indicates large potential for automated systems in maintenance and condition monitoring. We see that this technology is implemented to a large extent in other industries.

The drivers for the oil and gas industry has historically been based on improved safety. We see now a potential for both cost avoidance, reduced downtime and less impact on the environment

Maintenance and inspection is a large cost for the oil industry. In addition, these processes often cause shut down of the facilities.

Condition monitoring and maintenance is based on the actual status of equipment and systems. Today's technology makes it possible. In addition, robot technology has a potential for improving safety and reduce cost and downtime by avoiding human interactions.

The oil and gas industry has not been a front runner compared to other industries. The conservatism driven by safety and reliability requirements might be one reason to this. At the same time, we see a growing interest and a lot of initiatives and developments.

I have chosen to study topside static systems on offshore platforms. This to be able to narrow down the study. But in general, the descriptions, analysis and discussions may also be relevant for other systems.

Acknowledgements

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List of abbreviations

4D operations – Dangerous, Distant, Dull and Dirty operation

AR – Augmented Reality

CBM – Condition Based Maintenance

CM – Condition Monitoring

CUI – Corrosion Under Isolation

ENS – Engineering Numbering System

FA – Fully Autonomous

HSE – Health, Safety and Environment

IMR – Inspection, Maintenance and Repair

IO – Integrated Operations

IoT – Internet of things

LCC – Life Cycle Cost

MR – Mixed Reality

MTTF – Mean Time to Failure

MTBF – Mean Time between Failure

MTTR – Mean Time to Repair

NCS – Norwegian Continental Shelf

O&G – Oil and Gas

RO – Remote Operated

ROV – Remote Operated Vehicle

RPA – Robotic Process Automation

SA – Semi-Autonomous

UAV – Unmanned Aerial Vehicle

UGV – Unmanned Ground Vehicle

VR – Virtual Reality

1 Introduction

Automation and use of robot technology has developed very rapidly the last years. Technology trends indicates large potential for automated systems in maintenance and condition monitoring.

The question how this is being implemented in the oil and gas (O&G) industry and the potential for further development is interesting to study closer.

1.1 Background

Cost reductions and efficiency have never had more focus than today in the O&G industry. Essential factors in the offshore oil and gas industry is safety and efficiency. In an industry that experience lower margins than before, operational costs and production uptime become more important.

Efficient and improved routines for inspection, maintenance, repair and emergency handling ensure a continuous and robust production, reducing scheduled and unscheduled shutdowns. Increased uptime of production is a key point, and especially unplanned downtime. (GE oil and gas, 2016). Today´s inspection and maintenance approach include inspection rounds by on site personnel and data from fixed sensors. One way to increase the uptime of a plant will be to increase the number of sensors and routine inspections. This increase the maintenance need for the fixed sensors and expose personnel to potential risks. New technology trends indicate that we can resolve these easier with automation and robots. In the report "Havteknologi" from Holte et al. (2016), automation is listed by the industry and administration as number five for future priorities, while the field research and development consider automation as top three.

The development of digitization, robotics, automation and other ICT technologies have exploded the last decades. Moore's law predicted that the amount of integrated circuit computer power you buy for one dollar increased at a rate about a factor of two per year (Brynjolfsson and McAfee, 2014a).

Technology trends indicates large potential for automated systems in maintenance and condition monitoring. An industry in large change as the oil and gas industry, will benefit from reduction in maintenance and use of condition monitoring. There might be a potential for not only cost reductions but also such as improved safety, and environmental issues.

1.2 Objectives of this study

This thesis focuses on the improvement potential for the O&G industry by introducing more automation and robot technology. What are status today, where do we think we can get, and how can we get there?

The main focus will be on offshore topside static systems.

Important issues to be addressed are:

- Does the technology exists to implement automation in condition monitoring and maintenance today?

- What is the most important drivers/incentives behind implementing automation in inspection, maintenance and repair (IMR)?

- What is the overall opinion of automation in maintenance and condition monitoring on offshore topside O&G facilities?

- What is the main barriers for implementing automation?

- Look at the potential cost savings

Thus, I have chosen the following title of my thesis:

- Evaluation of the potential for automation and robot technology, with focus on condition monitoring on static systems for topside offshore facilities.

1.3 Limitations

In this thesis, I will limit myself to robotics and automation for maintenance and condition monitoring on static systems for offshore topside facilities. I will in general limit myself to technology relevant for the thesis as described above, but also mention other technologies. I will go more thoroughly into the most important technologies.

There exist various types of offshore platforms. Not all of them have a drilling unit, and they either produce only oil, only gas or both. This have an impact on what topside equipment is needed. Therefor I have chosen a concept with dry wells. Drilling equipment and systems will not be mentioned specifically but the analysis and discussions will be relevant for some drilling systems. Rotating equipment, such as compressors, turbines, pumps etc., is excluded in the analysis. This is to focus more

on inspection and monitoring of static systems. The analysis of risk based inspection will not be discussed.

1.4 Thesis approach

I have chosen to focus on research, literature and on interviews. I started with a broad literature search and then I screened the identified literature to focus on the most important ones for this thesis. There are a lot of different literature available and it has been important for me to limit the amount and extract the most important for this thesis objectives. Based on information from the literature I could establish topics important for me to discuss during interviews.

The interviews have been semi open which means that I have prepared the main questions but has been open to adjust my questions during the interviews dependent on who I interviewed, to not limit myself, see appendix A. Further I have used a strategic selection of interview objects to cover all main contributors. Interviewed objects from the Operators (oil company), contractors, suppliers and academia was chosen. They are all working with automation and robot technology. In addition to information they also guided me to more relevant literature and new interview objects.

The interviews have been both face to face and as telephone/skype meetings.

2 Theory

This chapter will focus on the basics of inspection and maintenance and some technology trends that are important in the future of automation and robotics.

2.1 Inspection and Maintenance

Inspection and maintenance philosophies have changed since the industrial revolution from a cost driver view to a to an asset performance view. This means that the inspection and maintenance strategy can increase the efficiency of a plant and add value. A further explanation of inspection and the maintenance techniques will follow. The inspection and maintenance techniques is to determine the condition of the plant and actions to maintain preferred operating conditions. This have become an essential part to avoid unplanned downtime of the plant.

2.2 Inspection

Inspection is defined as the action to determine the condition of the plant. Inspection offshore is performed by human either by visual inspection on different non-destructive techniques (NDT). This often require cleaning, venting or shutting down of the plant or equipment and are a cost driver.

2.3 Maintenance

Maintenance has become an important factor in the profitability of an asset. Maintenance philosophy´s have shifted since the beginning of O&G production on the Norwegian continental shelf (NCS). Today's view is that it can create additional value as an integral part of the business process. Maintenance is a combination of all technical, administrative and managerial actions during the life cycle of the asset intended to retain it to, or restore it to, the state in which it can perform the function as optimal as possible.

Failure of machines or equipment result in loss of production. The resulting downtime is very costly, and an important objective of maintenance is to reduce the downtime. Further breakdown of critical equipment and systems is a large safety concern especially related to integrity and barriers. In figure 1 we can see the most important types of maintenance. For the sake of this thesis, I will concentrate mostly on condition based maintenance (CBM). To get a better sense of the benefits of CBM, other

important maintenance types for the offshore industry will be mentioned, such as predictive maintenance, corrective maintenance, and reliability centered maintenance.

The strategies will differ between equipment and systems, ref critical versus non-critical and barriers versus non-barrier systems. A company´s maintenance strategy is most often comprised of different maintenance types, see figure 1.
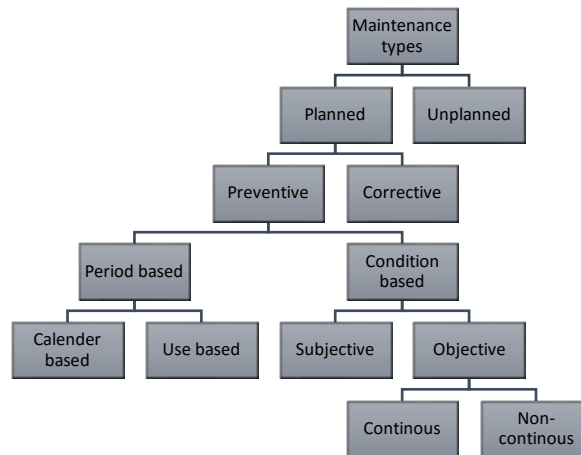
Figure 1: Maintenance types

The statement "Maintenance approaches do matter and yet companies rely on outdated maintenance approaches" given by GE oil & gas(2016) shows that the most frequent maintenance approach used today does not reduce unplanned downtime as efficiently as more modern approaches. Furthermore, only 24% of the surveyed operators explains their maintenance approach as predictive maintenance based on data and analytics. As many as 30% uses a reactive maintenance approach and the rest describes a planned maintenance approach(GE, 2016). A more modern maintenance practice will be condition-based/preventive maintenance based on data and analytics. This require a change in the "mindset" of operators.

2.3.1 Condition based maintenance

Planned maintenance is preferred. This means that maintenance is performed ahead of failure of the system. With planned maintenance, the avoidance of unplanned downtime is critical. Failures in equipment can lead to a dangerous working environment and is both time and cost consuming. Performing maintenance ahead of such failures is critical. Planning for maintenance can be based on the age of the equipment or how much it has been used. Or assess the health of the system, to know

exactly when it is not performing as preferred and thus identify the optimum time for maintenance. This is called *condition based maintenance.* Condition based maintenance or predictive maintenance has many definitions. But this type of maintenance is more than only maintenance, it is a philosophy or attitude that enhances the total plant operation by using the actual equipment or system condition in place.

2.3.2 Condition monitoring

Condition monitoring (CM) is associated with condition based maintenance, where the condition of the system or equipment is being observed and analyzed. The measurements assessed in comparison with past data relieve the condition of the system or equipment. The overall benefits of CM are to minimize the frequency and the consequences of equipment/system failure and to utilize existing maintenance resources more efficiently.

A good example is oil consumption in a car engine. The car has monitored the oil consumption, provided it the acquired oil and if the engine requires more oil than normal, it alerts the driver. This is an indication of engine failure; it is not operating in normal condition and should be dealt with. This can be fixed and is much cheaper than to run the engine until failure. The underlying factors behind this demand is increased quality expectations reflected in product liability legislation, increased automation to improve profitability and maintain competitiveness, increased safety and reliability expectations reinforced by legislation and reduced cost of maintenance due to less labor and material cost (Rao, 1996). These factors are also drivers today for more digitalization and automation, in maintenance and operations.

Development of CM systems is complex, and should be easy to operate and understand. Operators don't need another technical system to learn and deal with, and it is crucial that CM is effective and a value creator. Further it should be simple, robust and not introducing new risks.

Key futures of an effective CM system are links between the cause and the effects, systems with adequate response, mechanisms for objective data assessment. Storage and review of data, or big data will be explained later.

A CM system can be represented by two main areas; system set-up and review, and routine monitoring, assessment and diagnosis. System set-up and review identify critical equipment/system to be considered, detect how equipment/systems fails, finding the causes, effects and consequences of failure. FMECA (Failure Mode Effects and Criticality Analysis) is a suitable tool, selecting the appropriate CM technique, deciding where and how often to collect measurements, taking baseline readings and setting alerts.

The review is to perform these steps on several areas and find out if the CM system provides the relevant data to the actual operating state of the equipment/system measured. When the system give alerts is a critical step to review, if it is too sensitive it will alert the operators when it is not needed, if it is not sensitive enough the equipment/system measured will go to failure. The core of CM is the collection, storage and interpretation of data. See figure 2. The methods of assessing the data is level checking, measurements trending against time and compare measured data against historical data. As mentioned earlier, different techniques have an impact on the CM method chosen.
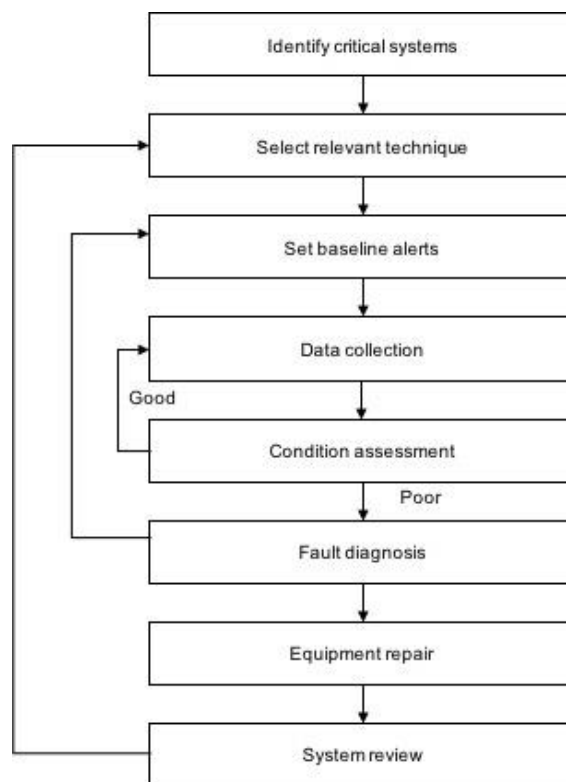
Figure 2: The process of condition monitoring (Rao, 1996)

Offshore facilities are built for human interactions. The human body is a complex system, and we have been given a unique set of senses to use. Humans have traditionally five senses; visual, smelling,

hearing, taste and touch. These are the basics for condition monitoring and humans can be a good resource to evaluate the condition of equipment and systems. In the modern times, these tasks can be digitalized and automated. Technological trends show that there exists a great potential in this area. Visual inspection is one of the most important tools. Video anomalies, e.g. missing or misplaced objects, detection of smoke and fire can easily be detected by visual detection by humans or through image or video processing algorithms. Thermography is a method to monitor the emission of infrared energy, i.e. heat. This is the feeling sense of the condition monitoring.

Infrared measurements are complicated because objects have three sources of thermal energy: energy emitted from the objects itself, energy reflected from the object and energy transmitted from the object. In a predictive maintenance program, we are interested in the emitted energy. With today's technology, it has become easier and less costly to distinguish these energies. This can either be executed by infrared thermometers which show temperatures on a specific spot, line scanners that covers a wider area in two dimensions and are limited in predictive maintenance and infrared imaging that are commonly used on complete machines, process systems or equipment.

Tribology is generally the term of friction and the consequences of this friction, and related to moving parts. The tribology technique is lubrication oil analysis, e.g. the car engine explained earlier.

Ultrasonic monitoring detects sounds. Where the human ears can sense sounds with frequency between 20 Hertz and 20 kilohertz, ultrasonic measure higher frequencies from 20 kilohertz up to 100 kilohertz. This means that it can detect sounds with higher frequency, i.e. it sounds like a "sizzle." Here we detect one significant benefit from modern condition monitoring. Technology can perform at a higher level than humans.

Vibration monitoring measures the change of the frequency of the vibration. In the same way as motion have been seen as displacement, velocity and acceleration, vibration have the same units, and can be used for monitoring the condition. If we detect abnormalities in vibration relative to equipment in "mint condition," the equipment does not operate in the preferred matter and can be heading towards failure.

Requirements for inspection methods is extracted from the recommended practice DNV-RP-G101: Risk based inspection of offshore topside static mechanical equipment. (DNV, 2010)

These inspection methods are:

GVI:	General visual inspection
CVI:	Close visual inspection
ET:	Eddy current testing
ET-remote:	Remote: Remote Field Eddy Current
MT:	Magnetic particle inspection
PT:	Dye penetration testing
RT:	Radiographic testing
RT-RTR:	Real time radiography
UT:	Ultrasonic testing
UT-Long range:	Creeping/Head Wave Inspection Method
UT-Tubes:	Internal Rotating Inspection System (Ultrasonic)

Thus, condition monitoring can be seen from two different angles; an industrial imperative towards more efficient maintenance and the technological improvements to measuring equipment and accompanying software.

2.3.3 Preventive maintenance

Preventive or period based maintenance philosophy is basically based on time. As seen in figure 1, either calendar based or operating hours. These numbers are often not random, and based on statistically data on mean time to failure (MTTF) and mean time to repair (MTTR). Where mean time between failures (MTBF) are sum of these two, MTBF are dependent on the operational environment. When MTBF vary we may have two outcomes; we either waste labor and materials on repairing or rebuilding equipment that does not need to be fixed that also lead to unwanted downtime, or the equipment run to failure and this type of maintenance are very costly.

2.3.4 Corrective maintenance

This can be to do maintenance when failure is identified or operation is deteriorated. This strategy may have huge consequences for safety and production uptime of critical systems. Thus, this strategy is normally not allowed for this type of systems. Further failure of a non-critical system may have impact on other systems, thus it is important to consider carefully before this strategy is implemented. In addition, it is necessary to be able to isolate the system not to cause reduced safety level or production downtime. This type of maintenance can be used for non-critical systems or systems with high redundancy.

2.3.5 Robotics in CM

The potential of robotics in condition monitoring is quite obvious. Robots have the potential of more accessibility of equipment, they can increase the number of measurements and give more accuracy of the inspection. Although robotics is seen as hardware, software robots is also important. The two in combination have the possibility of executing the condition monitoring tasks and have more accurate prediction of the measurements with better algorithms.

2.4 Technology trends

A legendary basketball coach named John Wooden once said, "We can have no progress without change, whether it be basketball or anything else." The offshore industry has become a competing industry where company's fight against small margins. An industry in need of change to improve. Increased productivity, efficiency and reduced cost is key points in this setting. Technology trends have shown that this is possible by taking new technology into consideration and use it as a value creator in the industry. The basket of all these digital-enabled technologies have several names, digital manufacturing and design or more known as "industry 4.0" and the "industrial internet" which includes technologies in production equipment (including robotics, 3D printing and adaptive CNC-mills), smart finished products (IoT) and data tools and analytics across the entire value chain (Nanry and Rassey, 2015).

As humans have developed, we have changed the way we live. Technology have given us the opportunity to evolve in a pace we have never seen. As mentioned earlier, Moore`s law predicted a doubling of the process capability of computers each year. Although his predictions may not be completely accurate, his predictions were remarkable correct. He actual foresaw the development of digital technology (Brynjolfsson and McAfee, 2014a). This technology has improved speed, capacity and ability to deal with complex problems and give a huge potential for further implementation.

In 2017 our lives are surrounded by technologies like cars, cell phones and computers. We are way beyond only thinking of digitization; digitization has enabled other technologies to change.

Digitization is the key in advancing technology. Technologies emerging today that we will both see advancing the O&G industry and peoples day-to-day life is digitization, automation, internet of things(IoT), big data and algorithms. These technologies have changed other industries in a significant matter. The complexity varies among industries, e.g. car manufacturing was maybe less complex to change to a more automated fabric than it is increase the automation on offshore facilities. We will go further into this later.

It is no doubt that "industry 4.0" can have significant impact on the value chain in offshore oil & gas. One factor can be the digital knowledge in the industry. The understanding of the technology and its business impact throughout the value chain. According to the study "Hindre for digital verdiskapning" (Waterhouse et al., 2013) Norwegians score above average on user competence, but lower on creating

competence in digital technology. Furthermore, Norwegians between 25 and 54 are below the European average on digital knowledge acquired through education. The age group 16 to 24 is even more behind. This go against the statements that the O&G industry in Norway has low technology knowledge due to an older workforce, see figure 3. Off course people educated in ICT-related studies have the required knowledge, but personnel educated in other areas may not have the required digital knowledge to see the potential of the digital industry in their field.
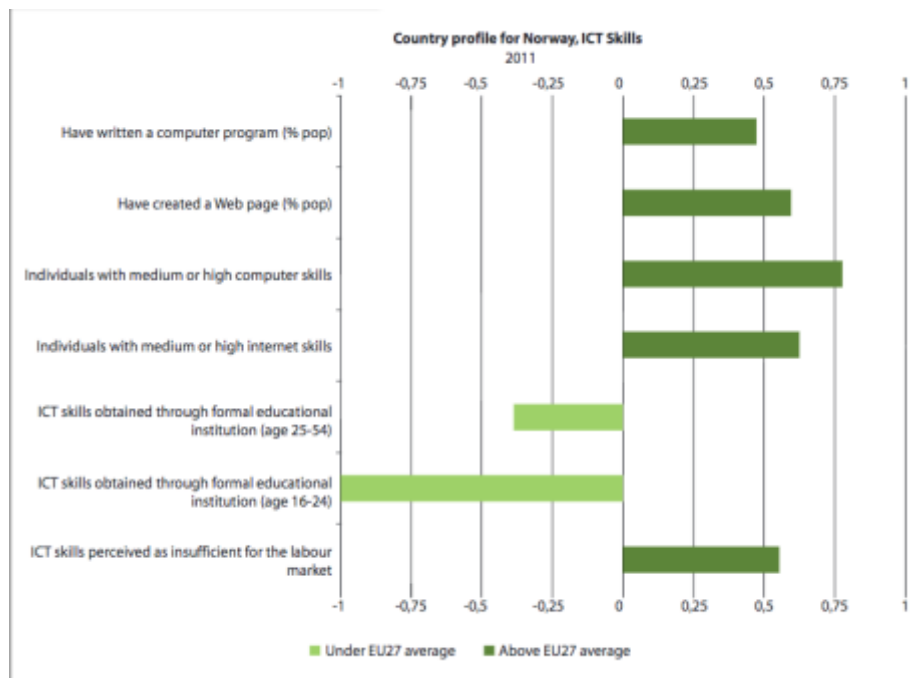
Figure 3: ICT skills(Waterhouse et al., 2013)

If we compare the statistics on digital competencies of the average Norwegians to the age of employees in the oil & gas industry, this does not support the fact that an older workforce is a barrier for digital value creation. Actually, we see from the figure above that the gap of formal ICT skills between EU citizens and Norwegians are bigger among younger people.

2.4.1 Digitizing and digitalization

Digitalization is enabler for other technologies mentioned is this thesis. Digitalization exists among us constantly. Companies today are rushing headfirst to become more digital. But what does "become more digital" means? There exist several definitions of the terms digitization and digitalization and it depends very much on the eye that see. Digitalization can be described in two ways, the technical view of the representation of information and how digitalization can be a value creator.

According to Dörner and Edelman (2015) the mind-set of being digital is about using data in a more efficient matter in decision making, devolving decision making to smaller teams, and to develop more iterative and rapid ways of doing things. Furthermore, they describe digital as a way of doing things, rather just a thing.

Digital content are data combined in such a matter that it represents a message, a story or an assembly of information that previous existed in and was described with reciprocal exclusive terms as text, picture and sound. Typical for digital content is that it is not protected to one specific software or hardware to be presented and made available to the user (DigitalutvalgetWaterhouse et al., 2013).

Digitalization is the usage of technology or communication services to offer existing service or product through digital platforms and/channels. (DigitalutvalgetWaterhouse et al., 2013)

According to Brynjolfsson and McAfee (2014a) digitization is the work of turning all kinds of information and media – text, sounds, photos, video, data from instruments and sensors, and so on – into 0´s and 1´s that are the binary langue of computer and their kind.

2.4.2 Automation

Automation is a technique, method or system of operating and controlling processes by electronic devices reducing human intervention to a minimum. It is one of the hot topics in today's lower-for longer environment. Thanks to digital advancements in big data, analytics and sensor technology, the O&G sector is now uniquely positioned to automate high-cost, dangerous and error prone tasks. This is not only to replace people, but to do work that is dull, dirty, distant and dangerous.

Further improvements can be made in areas such as maintenance planning and decision-making processes by bringing accurate real-time data to the right people, and optimizing production by using real-time well data to automate e.g. production rates, water injection rates and adjust gas lift flows.

2.4.3 Internet of Things (IoT)

Internet of Things(IoT) is network of devices, appliances, and other objects equipped with computer chips and sensors that can collect and transmit data through the Internet. With this opportunity, it is possible to connect devises and systems and look at use of automation and robots not only in each separate device or system but at the total topside functionality. There could be a big potential for design of future topsides when devices and systems can communicate with each other in and effective and reliable way.

2.4.4 Big data

Today we can collect data sets, typically consisting of billions or trillions of records.

30,000 sensors continuously generating data on a typical offshore oil rig. Less than 1% of the data generated is used to make decisions. To be able to utilize these data in an efficient way it is important to look at the needs and potential to use these data in and efficient way both to; learn for new platform designs, minimize downtime and improve safety for existing platforms. Due to the huge availability of data it is important to be able to extract relevant data not to be overwhelmed of the possibility to collect data. Today's technology should be able to assist us in doing this.

2.5 Maintenance management

Maintenance management is; administrative, financial and technical framework for assessing, planning and executing maintenance operations on a scheduled or planned basis. This should as mentioned earlier be seen as a value creator and be part of the business process and an important factor for the profitability of an asset. Automation and robot technology should be important factors when establishing new maintenance strategies and review of strategies. An important factor for maintenance management process is to establish what you want to achieve, analyze the potential and identify main contributors. It is important to establish the main principles in the design phase because design will have a major impact on the maintenance philosophies and strategies e.g.; type of material, degree of automation and conditioning monitoring system, sensors, system robustness/sparing philosophy (1x100%, 2x50%, 3x50%) etc.

2.6 Integrated Operations (IO)

In the Petroleum industry, Integrated operations (IO) refers to new work processes and ways of performing oil and gas exploration and production, which has been facilitated by new information and communication technology.

The rapid development of this technology makes it possible to reduce the silo thinking and further develop multi-discipline collaboration in plant operation with production is focus.

The automation and robot technology development will be a very important basis for developing integrated operations.

2.7 Life cycle cost (LCC)

Life cycle cost is the total cost of the ownership over the life of an asset. This include all cost related to the lifetime of an asset including financial cost, environmental and social cost. It also covers the capex elements such as; planning, design, construction and commissioning. Operations, maintenance and disposal is also included.

Operation and maintenance will be a major part of the cost.

Oil companies include life cycle costs analysis in their concept selection process, evaluation of maintenance strategies and during selection of equipment and sparing philosophies.

3 Digitization and automation in the offshore O&G industry

The aim, in almost all industries, is to have a high level of automation to increase productivity and efficiency (Skourup and Pretlove, 2009). In the manufacturing area, we see a large impact in the use of this technology. To automate operations, industrial robots is an important technology enabler on the way of reaching this goal. In different industries, automation have the biggest potential in repetitive routine tasks, which may be heavy, dirty, dangerous or otherwise better suited to a robot than a human.

These incentives have come to light in the offshore oil and gas industry. Robotics and automation is used in the O&G industry, but with the main goal of increased safety. The industry has generally only automated processes that are either difficult or impossible for people to perform, or would dramatically improve HSE. Examples of applications are remote operated vehicles (ROVs), automation of drilling operations and intelligent pigs. As these are important goals of the industry, the applications are often associated with a dip in the production. As the industry is in a challenging time with huge cutbacks, the focus on profitability and efficiency has increased. High margins have created a "production-for-all costs-culture." But with lower margins as we experience now, the industry shifts their focus towards efficiency and profitability. We see an increased interest from the O&G companies in the use of robotic technology and automation, exactly with the incentives of increasing the profitability, efficiency and HSE. Further we see an extremely fast development in robot and automation technology which increase the potential for all industries including the oil and gas industry.

3.1 Drivers behind automation and robotics

The main drivers for automation and robots is cost efficiency, safety issues and production regularity This include handling of available data in a fast and reliable way to optimize maintenance and operation. This will contribute to cost effective operation and maintenance and improve the safety for the asset and people. By introducing robots, it will also reduce the need for people offshore and thus reduce labor cost. Further this contribute to improved production regularity. Safety wise the improvement will both be on regularity of safety critical systems and reduced human exposure to hazardous areas and situations. In addition, this will improve the environmental performance by reducing toxic waste, avoid leakages and catastrophic events.

Thus, the main drivers for automation and robotic will be (figure 4):

Figure 4: The most important common drivers for decision making in the petroleum and (petro)chemical industry (Hoorn et al., 2017)

3.2 Criteria´s for robotics and automation in the O&G industry

In the chapter above repetitive tasks was emphasized as applicable to robotic process automation (RPA). Transeth et al. (2013) identified this area together with 3 others. 4D: dangerous, distant, dull (referred to as repetitive) and dirty. Dangerous areas where the risk of fatalities is high, e.g. flare towers or emergency handling after gas leakage. Platforms today often plan for minimum permanent manning and robots make it possible to move offshore personnel to onshore facilities. Inspection and cleaning of tanks is an area where it does exist robotic solutions. This can also go under the category of dangerous areas, because the HSE challenges creates time and cost consuming operations (Ramsdal, 2016).

In most workstations, many tasks that are executed by humans are repetitive and pre-defined. Dull, frequent, simple and routinely executed tasks are an especially interesting area to apply robotics and automation (Pfeiffer et al., 2009, Transeth et al., 2013). Such tasks have been automated in large scale in factories. E.g. where a person places jelly jar´s on the conveyor belt in a factory and the rest of the process is automated. This step is highly repetitive, and was later automated. (Brynjolfsson and

McAfee, 2014b). The same jars are picked up, and put on the same conveyor belt each time, an infinitely times.

Below, in figure 5 is an example where a set of guidelines and criteria's that can clarify the use of robot process automation (RPA).

1. Standardization
- Identify repetitive, simple tasks that acquire unnecessary large amount of time.
- Can the identified tasks be mapped as end-to-end processes with predefined inputs?

2. Digitization
- The process can be digitized and processed by an algorithm
- Can the process be executed by a robot on demand by an event or schedule?

3. RPA
- Does the task require any decisions made by human intervention?
- Are the processes changing frequently or are they stable?

Figure 5 Roadmap to robotic process automation.

The first step is to clarify which tasks that are applicable to RPA. As we see in figure 5, step 1. If it possible to predefine the inputs, the tasks can be digitized with the binary language and processed by an algorithm/computer. The software part is now established. A program can now execute the tasks; it has a brain. Further for physical tasks, robots can be the physical body performing the task. Especially in industrial areas, such as offshore topside facilities, that are designed for human intervention, this is applicable. Take for example inspections of pipes on offshore facilities. They are planned, and the personnel know exactly when to execute them. In CM context, robots can apply 24/7 surveillance of the pipes, and initiate inspections on demand.

To automate these tasks, we can identify several advantages. Repetitive tasks tend to be less interesting to carry out for personnel, this can cause personnel to not focus 100 percent on the tasks and accidents or failures may occur (Transeth et al., 2013). A robot doesn't have the choice to focus less on some tasks. Routine inspection tasks of pipes on topside facilities are a good example of this. The piping system is complex with a large area to cover. Robots have the advantage that they will execute the task in the exactly same way every time, that have been programmed in advance. Data collected from one measurement can then be compared to older data from the exact same measurement. Furthermore, robots can operate at all times. More frequent inspection leads to a higher level of monitoring that may detect failures at an earlier stage and this may lead to less downtime.

3.3 Near future robotized tasks

Such tasks mentioned above are found on topside offshore platforms. Pfeiffer et al. (2011) identified production operation tasks that could be executed or assisted by robots and establish technical feasibility in the offshore environment. First, they identified and ranked production operation activities based on data from two offshore platforms, one producing gas and one producing oil. Their study, categories activities regarding application of existing and near future robot technologies. These categories are (Pfeiffer et al., 2011):

A) Activities which can easily be "robotized" using 'off-the-shelf' robotic technologies with no application specific modification required.

B) Activities which could easily be "robotized" using existing robotic technologies and with standard application specific modifications.

C) Activities which could potentially be "robotized" using robotic technologies, but would require application specific adaption and further development of current robotic technology.

D) Activities which cannot be "robotized" using current or near future robotic technologies, but would benefit significantly from "robotization" and could be a subject of future research and development.

Different robot tasks/activity descriptions were established and linked to a robot concept, and categorized accordingly to above mentioned categories. The findings they focused most on, and most relevant for this thesis is three versions of a Mobile Universal Service Robot. The different versions will perform assistant roles, autonomously task excluding manipulation and autonomously tasks including manipulation. These are accordingly categorized B, C, D. Their further research develops a

version 2 robot, meant for activities that does not need manipulation, in mind that manipulation can be a further development of the same robot.

In Total E&P´s ARGOS challenge for mobile robot's concepts, the tasks did not include manipulation with the production equipment. It is stated that *"These robots will be capable of performing inspection tasks, detecting anomalies and intervening in emergency situations"* (Total, 2015).

A rail-guided robot, called DORIS, supported by Statoil and Petrobras, is designed for inspection and monitoring tasks. But as mentioned by other´s, the aim in the future is also to perform simple intervention and sampling tasks (Carvalho et al., 2013).

Research conducted shows that tasks that are focused on being autonomously executed by robots is inspection and monitoring tasks without manipulation. Simple manipulative activities are the next step in autonomously robotics. All off these tasks mentioned applies to tasks that can be mapped as an end-to-end process with predefined inputs, i.e. where, how and when to execute inspection rounds of certain systems can be mapped as an end-to-end process with predefined inputs. Many manipulative tasks are also standard tasks that can be executed as an end-to-end process, and when specific activities are identified, they are likely to be autonomously executed by robots.

Activities on offshore platforms are scheduled on a daily basis or occasional operations. The scheduled daily tasks are planned, often pre-defined. Such tasks are:
- Inspection
- Monitoring
- Simple maintenance

Common occasional operations that is pre-defined, can be tasks connected to gas leakage, identify and locate fires and valve and lever operations. This can identify and locate gas leakage, shut down unsafe operations, secure area and stop the leakage. These operations increase the safety on O&G platforms, and are applicable to robots.

3.4 Systems for automation

In the chapter, above repetitive tasks were emphasized as applicable for RPA. We can locate systems relevant for such repetitive tasks. In this thesis, limitations are set at inspection for topside systems. The topside of a platform includes all equipment on the surface deck and the main modules located here are:

- Living quarters
- Utility area (power generation, air supply, water treatment, chemical systems and other utility functions)
- Drilling (mud systems and drilling equipment)
- Wellhead area
- Process area (separations, treatment, pumping/compression)

Platforms are designed to specific field specifications, and the required modules may vary from field to field. It exists platforms with only one main function. E.g. platforms for accommodations and pure drilling rigs are commonly used. An overview over a common setup of functional areas and the flow of gas and liquids is presented in figure 6. The wellhead area will be discussed more on the next page, this is where the oil and gas arrives from the wells. The processing area includes separation, gas treatment and compression, oil treatment and pumping, water treatment and water injection. This is the area where the hydrocarbons are processed. From figure 6, we can see that gas and water can be injected back into too well to maximize the recovery of oil and gas. The utility areas are all supporting systems required for the production, e.g. safety and firefighting systems, power systems chemical systems etc. In addition, most platforms have living quarters.
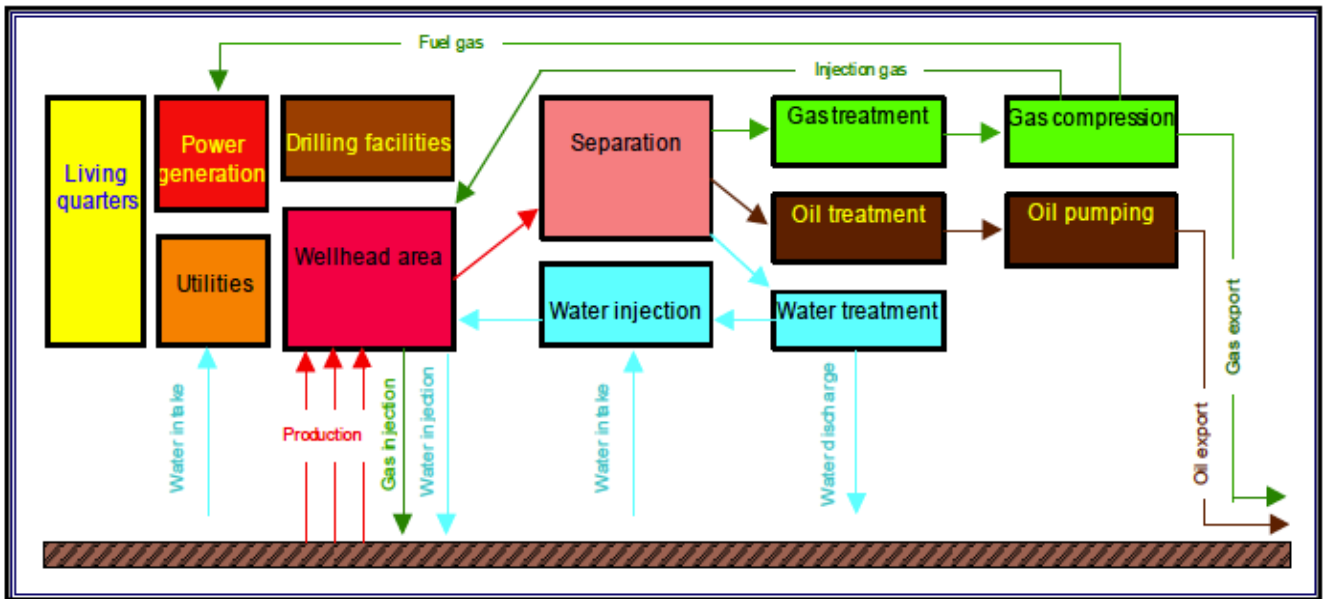
Figure 6: Functional areas and the flow of gas and liquids. (Odland, 2015)

Engineering Numbering System (ENS) was established as a comprehensive and systematic coding system to define platform systems. Such coding system is explained in NORSOK Z-DP-002. These systems can be, on a fully integrated platform, categorized into 3 main groups. Drilling and well related systems, process and process support systems, safety and utilities system. In figure 7 a simplified overview of the production systems is shown.
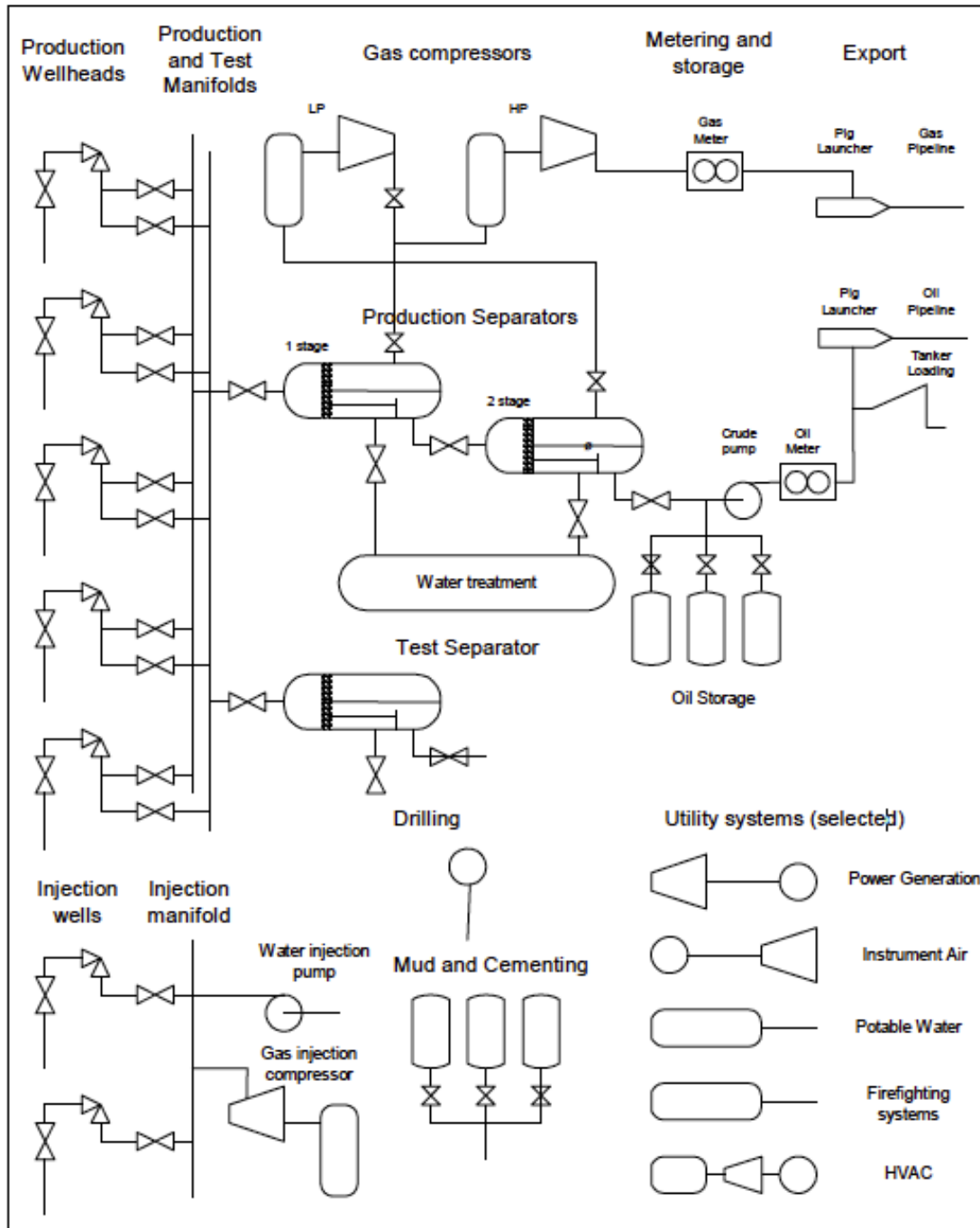
Figure 7: Oil and gas production overview (Devold, 2009)

Drilling and well related systems

The wellhead is set on top of the well, and consist of the casing head, tubing head and the "Christmas tree." This can either be dry or subsea completion. For the sake of this thesis, we concentrate on dry completion on the topside structure of an offshore platform. The choke regulates the flow of hydrocarbons. Tubing and casings are what brings the hydrocarbons from the well. The pressure of the hydrocarbons can be extremely high and must be confined and controlled. This is where the

"Christmas tree" has it function as a main safety barrier. Here is the tubing head and casing head connected with a set of valves and gauges that must be able to tolerate pressures up to 140 MPa (1400 Bar)(Devold, 2009). The Christmas tree constitute several high-pressure valves and gauges. More specific these are; The master gate valve, the pressure gauge, the wing valve, the swab valve and the variable flow choke valve. These valves have different functions and are both manually or remote operated. The manifolds gather the well stream from each well and guides it either to a test separator or to the actually separation process. We can see from figure 7 that in this area, there is a vast number of valves and pipes that need inspections, and the area deals with hydrocarbons with high pressure and thus need monitoring.

Process and process support systems

The process area is where the oil and gas is treated on the platform. Here oil, gas and water is separated from each other and stabilized. This can be done in several stages. The crude handling and metering system shall measure and add pressure for the oil to be exported. Pumps, meters, pipeline export or storage and pigging facilities are located here. Systems for gas compression and re-injection, gas treatment, gas condition, gas export and metering and gas sweetening are also located here. High temperatures and pressure is present, which enhance corrosion of equipment. These systems contain a lot of pipes, flanges and valves that need monitoring.

Safety and utilities systems

In the safety and utility systems, there are a vast number equipment required in a production facility. Some of these systems are sewage treatment, cooling and heating mediums, chemical injection, fuel gas and hydraulic power. There are a lot of processes in the utility module that need inspection and monitoring, e.g. pipelines, valves and gauges.

Safety systems are very applicable for robot's technology implementation. Either the robot can be a part of the safety system, executing fire and gas detection and emergency handling, or do inspection and maintenance of the safety system.

Figure 8: Adequate space must be provided around machinery, tanks, vessels, and pipe-headers. (Odland, 2015)

As shown in figure 8, offshore topside facilities are complex sites surrounded with heavy duty equipment. As discussed in chapter 3.2 we are looking for systems that require pre-defined tasks that can easily be digitized. Equipment that located on platform topsides are found to be pumps, valves, gauges, pipes of different dimensions including flanges and fittings, storage tanks, compressors, manifolds etc.

The tasks focused in chapter 3.2 was inspection, monitoring and simple maintenance tasks. Robotized execution of tasks is especially applicable for:

- Pipeline system (Of different dimensions)
- Flanges and fitting
- Remote operated valves
- Gauges
- Safety systems (Fire and gas systems)

3.5 State of the art offshore robotics

Robotics and automation is already used in the O&G industry, but with the main goal of increased safety. The industry has generally only automated processes that are either difficult or impossible for people to perform, or would dramatically increase HSE issues. Examples of applications are ROVs, automation of drilling operations and intelligent pigs. As these are important goals of the industry, the applications are often associated with a dip in the production (Skourup and Pretlove, 2009).

As the industry is in a challenging time with huge cutbacks, the focus on profitability and efficiency has increased. High margins created a "production-for-all costs-culture." But with lower margins, the industry shifts their focus towards efficiency and profitability. And we now see an increased interest from the O&G companies in the use of robotic technology and automation, exactly with the incentives of increasing the profitability, efficiency and HSE.

Following are some ongoing projects both from the industry and from research and development in mobile robotics for offshore topside inspection and maintenance.

The Fraunhofer Institute of Manufacturing Engineering and Automation (IPA) has developed and tested one of the first prototypes of robots for inspection for offshore facilities, MIMROex. This research is an ongoing development with clear goals of each step. This robot was tested 12 hours/day for 10 days on an offshore gas platform, shown in figure 9. The test focused mostly on navigation and safety concerns and environmental conditions (i.e. harsh weather.) A robot concept to execute tasks autonomously, not included manipulation. To be tested on an offshore platform, stringent safety requirements was mandatory. A factory acceptance test was required.

Production areas involving hydrocarbons are considered as explosive environments, and high safety and certification is required. Mapping was 50 percent of the test, and for localization, the robot uses shapes such as pipes and poles, and reflecting tapes applied around the area to be mapped. This resulted in a 95 m x 135 m area with 170 reflector poles, 50 pipes and 720 thin pillars. (Pfeiffer et al., 2011).
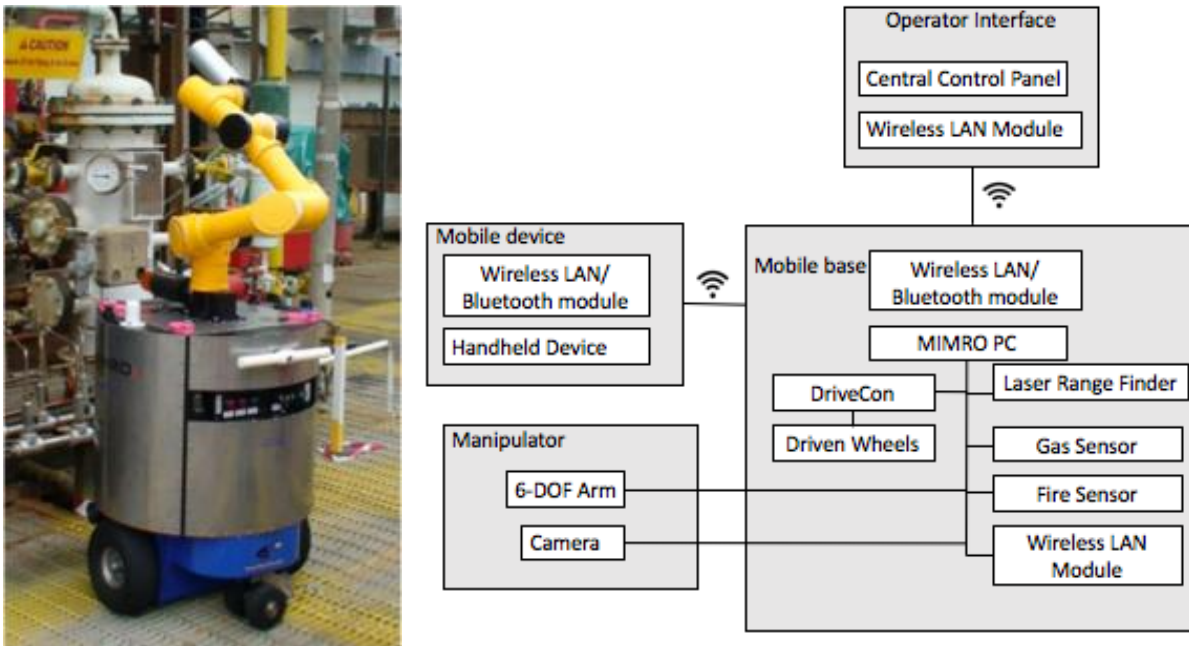
Figure 9: MIMROex robot(Pfeiffer et al., 2009, Pfeiffer et al., 2011)

The hardware set-up is presented in figure 9. The "body" of the robot includes a computer (the "brain"), driving unit, and sensors such as stereo microphone, gas and fire sensors and laser range finder used for mapping the environment. For visual inspections of equipment, a 6 degrees of freedom (DoF) arm with a camera attached to it is used. It uses wireless LAN and Bluetooth to communicate with the central control panel and a mobile device, see figure 9. Predetermined tasks can be thought to the robot by personnel through the mobile control device. Data from specific inspection points or from continuously monitoring is sent to the operator control panel. The result of testing offshore shows that 50% was used for mapping, 15% of the time was used for teaching and performing inspection tasks. Bad weather resulted in 10% lost time, no personnel was allowed outside. And 25% percent of the time was lost due to software and hardware failure. With this test, they proved the version 2 mobile robot, mentioned in chapter 3.3. It can perform inspection tasks successfully and be ordered to a location on the map, and autonomously get there by itself.

Sensabot (figure 10) is a robot developed at the Carnegie Mellon University, supported by Shell. This robot is designed primary for extreme weather conditions. The Sensabot was the first robot to be approved for use by oil and gas companies. The electronic equipment meets the international electronical commission (IECEx) standards and satisfies the ANSI safety standards. It can get through passages designed for human, and move between multiple levels with installed ramps, cog rail systems and elevators. The Sensabot is equipped with a wide range of sensors connected to a sensor boom and

perform on a human level. The robot removes human from the hazardous operation environments and relocated them to a safer control station. This Sensabot is a human´s senses out in the field.

Figure 10: Shell´s Sensabot(Ward, 2016)

The latest contribution to inspection robotics for offshore platforms comes from the ARGOS (Autonomous Robot for GAS and Oil Sites) challenge arranged by Total E&P. In 2014, 5 teams were selected to develop robots that would go through 3 years of qualifications, before one was selected as the winner. The team called AGRONAUTS was in May 2017 announced as the winner, and will start operating on Total E&P´s industrial sites in 2020 (Total, 2015), see figure 11.

Figure 11: The Argonaut(Bagnoli and Wocko, 2017)

It is a belt-driven robot designed for hazardous environments. This is a further development of the unmanned ground vehicle (UGV) – Taurob tracker (Taurob, 2017). It is certified for explosive and waterproof environments, so it is very applicable for the offshore environment. This mobile robot is designed for a broad set of assignments, with easy add-on integrations of measurement devices and sensors. The original Taurob is designed with a 6 DoF manipulator, but the ARGONAUT did not need the manipulator in the ARGOS challenge. This shows that manipulation tasks are possible. They won the challenge with high quality performance. The algorithm for relocation and localization performed with 1cm precision, the 3D simulator is suitable for safe operations and maybe the most important point, very easy to use. Switching between autonomous mode and remote operated mode was very fast and efficient. (Total, 2017)

DORIS (figure 12) is a research project that is supported by Statoil and Petrobras, which have as goal to design and implement a mobile robot for remote inspection, and data acquisition on offshore facilities (Carvalho et al., 2013). The aimed tasks are inspection, monitoring and intervention. This results in a rail guided robot, with cameras, microphones, gas, vibration and temperature sensors, and a manipulator arm. The manipulator arm will perform machinery diagnosis, read process plant instruments, and perform interventions on valves and equipment. As a rail-guided robot, the path is pre-determined and the robot can operate in a 3D environment. The rails are simple construction and comes in modules, which give the opportunity to adapt the system to each field. The robot itself it modular, with 4 modules as the default configuration, but this can be adapted to the specific environment.

Execution of tasks can either be performed autonomously, pre-scheduled, or manually by personnel in real time remote operation.

For the real-time system operation, there exist a framework:

1. The first step is for an operator to validate one complete lap to set these signals as reference signals.
2. Following signals collected by the robot is compared with these reference signals to detect anomalies.
3. The system operator can set new reference signals using a simple update procedure, after which the system goes back to operation.

Sensors considered for DORIS are: fisheye camera, high-resolution camera, infrared camera, which also provide temperature information, stereo camera, microphone array, gas sensor and vibration sensors.

Figure 12: The DORIS mechanical design, showing a straight section of the rail with a support, the traction module, the passive module and a double Cardan joint used to couple the two modules.(Carvalho et al., 2013)

Robotic arm Telbot

This is a robot arm with high pressure cleaning of tanks. The product is named Telbot and is developed by Oil service company Prezioso Linjebygg together with Statoil, Total, Gassco, Wälischmiller Engineering and Forskningsrådet. (Ramsdal, 2016)

Personnel do not need to enter the tank and thereby the downtime is reduced. Further you save a lot of time for preparations and reinstatement. In addition, it reduces the risk through avoidance of personnel into the tanks.

The arm has a range of six meters and can be either preprogramed or remote operated. The robot is IECEX- certified and can operate in hazardous areas containing explosive atmosphere.
The first generation of Telbot is used at Shells facilities at Nyhamna.

EMIS

EMIS is a mobile app that simplify the inspection of pipes. This is developed by ENGIE and used at the Gjøa platform. The goal was less reporting and more inspection. Before the inspectors used 80% of the time for reporting and 20% for inspection. Now it is the opposite with 80% inspection. That

give them more time for more inspection and quick feedback to the onshore organization. (Andersen, 2016)

The APP give the inspectors access to data and work orders in the field. The PAD used is certified for explosive environments. Results can be saved directly and the engineers onshore has immediate access to perform their analysis and make decisions. ENGIE claim that this process previously took up to two weeks.

UAV (Unmanned Aerial vehicle)

This is Drone technology and is already in use e.g. for inspection of flare boom and other inspection in height where it is difficult or time consuming for people to enter. This technology is so far mainly used for inspection purposes. The experience from usage of drones is their lack of capabilities in congested areas.

Using UAV as an example can avoid huge amount of unnecessary work related to scaffolding and possible restrictions or closing of areas.

4 Analysis and findings

While the O&G gas industry is experiencing lower oil prices, the focus on lower cost of production have increased. Developments in technology suggest that robots can reduce the downtime of the assets. At the same time the O&G industry have been a conservative industry. What works today is good enough for tomorrow. To evaluate the development of robots for topsides on O&G platforms, the experience both from the robotic perspective and from the O&G industry is important and have been conducted through several interviews. In addition, literature regarding the subject has been conducted to help determining the possibilities and future of robots for topside static equipment on offshore platforms. First the drivers are identified to get an understanding of the future development of this field. Further is a set of criteria´s for inspection methodologies discussed to clarify the what is expected by robots today.

4.1 Drivers in the O&G industry meets benefits from robots

Improve safety, environmental performance, increase operational efficiency and cost avoidance and reduction is listed as the main drivers behind decision making in the O&G industry. These drivers are important in light of future developments and goals.

4.1.1 Safety improvements

Human safety on offshore installations is a vital factor in this industry. Robots can remove the risk that humans are exposed to. Through the interviews, safety is said to be the most important driver behind the use of robots. To keep the personnel out the harm's way. The personnel operate in confined spaces, such as pressure vessels and tanks. This require safety measures that is time consuming and cost driving also. Offshore installations are a dangerous workplace, where the personnel are working at height, in contaminated areas, with hot equipment or in hot areas. Robots have the potential to remove the humans from such environments.

4.1.2 Cost avoidance and reduction

Avoid and reduce actions and operations that have high cost is important. Such tasks are often related to the preparations for human entry, such as scaffolding, cleaning of equipment and taking the asset offline due to inspection and maintenance.

4.1.3 Increase operational efficiency

Downtime is mentioned several times in this thesis, and the reduction of downtime is the key to increase operational efficiency. In many cases, inspection and maintenance requires that the equipment is offline. This often lead to a shutdown of the production, which robots could avoid.

4.1.4 Environmental performance

Environmental performance is important for the O&G industry. This is the prevention and reduction of pollution. To avoid leakages is important and to reduce the impact of a leakage. To see the benefits from robots impacting the environmental performance is not very clear. The systems to be inspected and maintained must often be cleaned on beforehand. Robots that can operate in dirty environments and can thus remove the need of cleaning equipment and systems which can lead to toxic waste.

4.1.5 Activitys and drivers

The customer proposition from sprint robotics (Hoorn et al., 2017) suggest 8 activities that are seen as the most important concerning safety, cost and environmental issues in the context of inspection and maintenance of static equipment on topside offshore facilities. To remove or reduce the need of these activities is the business objectives in this context.
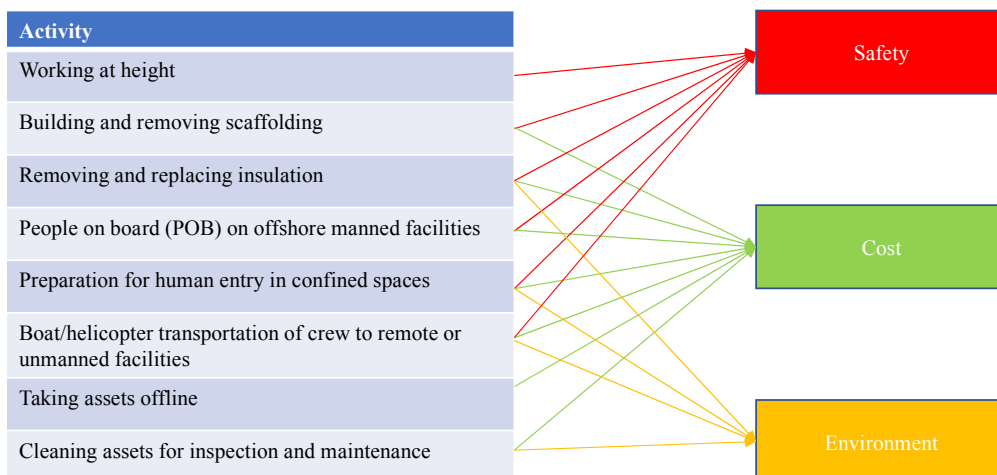

Figure 13: Expensive activities in terms of identified drivers (based on Sprint robotics (Hoorn et al., 2017p. 15-16))

Previously, cost avoidance and reduction and operational efficiency have been described as to different drivers, but they are two sides of the same coin. Taking the asset offline means to shut down the production. This is reducing the total production, i.e. lower operational efficiency which is costly. These drivers overlap with each other also. For instance, if you use robots for certain inspection tasks this may remove the need of scaffolding, cleaning of equipment and venting of the equipment. This again remove the risk humans are exposed to. For example, heights and hot equipment. Further this also remove operations that are time consuming.

Increase safety is mentioned above as the number one driver in the oil and gas industry. Interviewers stress the need of removing humans from dangerous environments as the most important driver behind implementing robots. From figure 13 we can see eight activities identified by SPRINT in terms of the above-mentioned drivers. This present alongside with the interviews that the main drivers are increased safety and cost reduction and avoidance. The focus from the industry does not seem to be towards the environmental aspect, but this is an important area in the community today and will be a more visible driver in the future. From figure 13 we can see that there exists an environmental gain for these activities with robots and can play a role in the future.

4.2 Criteria´s

One important fact for robots is that they have to work in the real world, not the ideal, clean and organized environments that laboratories often is. Offshore topsides operation areas are highly complex environments consisting of pipes, general equipment and random obstacles. This challenge is recognized through literature and interviews as the most important obstacle for robots. This pose the question whether to develop robots for such environments, design the environment more robot-friendly or a combination of these two. Further, this chapter presents key findings of barriers that set the requirements for the technologically development of such robots.

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                          ┌─────────────────┐
                          │    Criteria´s   │
                          └─────────────────┘
            ┌──────────────────────┼──────────────────────┐
  ┌─────────────────┐    ┌─────────────────┐    ┌────────────────────┐
  │    Mobility     │    │ Inspection Method│    │ Operational efficiency│
  └─────────────────┘    └─────────────────┘    │     and safety      │
                                                 └────────────────────┘
```

- Direction of viewing
- Operational area
  - Multiple levels
  - Steps
  - Slopes
  - Confined spaces
  - Range of surfaces
  - Heights

- Sensors
- CVI
- GVI

- Uptime
- Battery range
- Temperature range
- Water proof
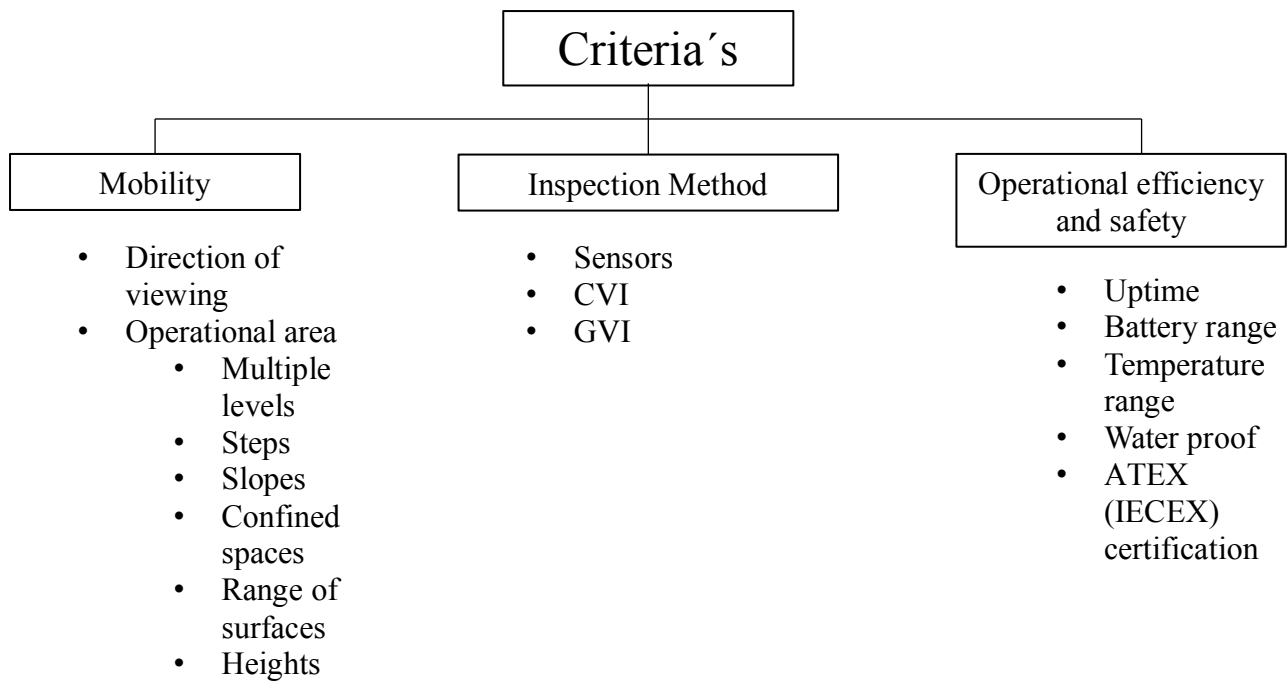- ATEX (IECEX) certification

Figure 14: Criteria´s for robotics for inspection and maintenance on topside offshore facilities

The O&G industry have high requirements for equipment before using them. This is mostly induced by high safety regulations, because of operation in highly explosive atmospheres. There have been identified several important factors to take into consideration: mobility, inspection method and operational efficiency and safety. See figure 14. Here the operational efficiency and safety is linked to the robot. Mobility have been mentioned before and is the most important barrier towards the development of robots. Mobility is important due to the complex area of operation, and the diversity of the environments of topside offshore facilities. The inspection methods to be chosen is an important factor to look at to ensure that the results reflect the correct condition of the equipment inspected. This require sensors and some kind of visual inspection. The environments in this context induces the danger of explosions and thus sets requirements for the technical development of these robots. This will be presented together with the operational requirements for the efficiency of the robot. Robots will do no good if its only working part time.

4.2.1 Mobility

Offshore topside environments are described in chapter 3.4. Figure 8 represents an example of the complexity of such facilities. Offshore platforms have been designed for human interaction with the equipment. If we compare this environment with the production line found for example in the car industry, we can see that the environment sets completely different requirements.

As we can see from the chapter state of the art, the Sensabot, MIMROex and the Argonaut are all designed to operate on the pathways. I.e. on walkways and surfaces where humans can operate. The MIMROex is designed with wheels and cannot operate on different levels unless there is installed special designed infrastructure. This also apply for the Sensabot. The Argonaut robot is designed to move up and down stairs. As stated earlier the topside is a 3D environment. The only robot found in the research to fulfil the criteria of reaching height is the DORIS robot. This again requires new infrastructures, the rail. The rail can be placed where the personnel wants it to operate, given enough space. Most of the robots looked at have a manipulator or an arm to place the sensors, but none of them have the sufficient length of reaching heights.

Scaffolding and general working at heights have been seen as two important areas for robotic developments. Inspection of the flare is one example of this, here unmanned aerial vehicles (UAV´s) have been used with great success. AUV´s have been considered for the inspection of other equipment on the topside also. Here several obstacles have been discovered. One of these is dense pipe racks, where other solutions is mentioned as crawlers and snakes. This reflects the diversity of the equipment, where one solution will not be able fulfill all the needs.

Hot spots

When considering the inspection of offshore topside static equipment, hot spots are areas where damage is most likely to occur (DNV, 2010). These hot spots are a result of different kinds of degradation. Types of corrosion, erosion, corrosion under isolation (CUI), mechanical damage and fatigue damage are common degradation found on topside equipment.

Areas where degradation is expected to occur are dead legs, areas where water can cumulate easily or drips onto piping (low points, water entry point and corners), pipes and vessels exposed to water condensate, welds including heat affected zone (HAZ), control valves, flanges, screwed connections and unpainted surfaces or where paint is in unwanted condition. DNV (2010) explains this in a more detailed matter. DNV (2010) relate each degradation mechanism to inspection methods explained in chapter 2.3.2. The most common inspection methods are found to be CVI, UT, RT and ET. Information collected from the interviews also relieves that the equipment condition can be found by using these methods.

Direction of viewing

The total equipment set-up is not alone complex, but the inspection methods are complex in its own matter, e.g. weld inspection. To achieve the correct result, direction of viewing should be applied parallel to weld, perpendicular to the piping surface and for corners the inspection is preferred to be applied both parallel and perpendicular.

If pipes and other equipment have limited space in-between, to apply the correct direction of view can be difficult. This pose the problem of complexity of the topside environment.

This further pose the problem whether it should be developed more technology that can fulfil this need or build more robot-friendly environments. A statement conducted from the interviews explains that to design the topside for robots will require space. The topside must become more like the organized and clean laboratory. More space on topside equal more weight, this is not preferred. Especially because it is a cost driver. Here is the life cycle cost analysis important. What will the savings in term of safety, environmental and cost, compared to extra potential cost.

4.2.2 Inspection method

DNV (2010) relate each degradation mechanism to inspection methods explained in chapter 2.3.2. The most common inspection methods are found to be CVI, UT, RT and ET. Information collected from the interviews also relieves that the equipment condition can be found by using these methods. Some of these are already in use, but they are deployed by human personnel.

4.2.3 Operational efficiency and safety

For operational efficiency and safety there is two crucial criteria's. ATEX (IECEx) certification of the robots is required(Total, 2015, Hoorn et al., 2017, Pfeiffer et al., 2009). This means that the robot is explosion proof. Harsh weather is also an important factor. Splashes of salty water give a high probability of corrosion. Temperatures can differ between locations, from up to 50 °C down to -30 °C. Additionally humidity up 100% and exposure to direct sunlight can be factors on some offshore facilities. Barents Sea, located north of Norway, is expected to be a future for O&G companies. One proposal for such platforms is unmanned facilities, which will be a domain especially applicable for

robots. This especially pose a problem for robots and may require the offshore platforms to be designed according to robot needs.

The operational efficiency of the robots is identified as a requirement especially from the Operators. The time not capable of operating is essential here. As mentioned in chapter 3.5 the test of the MIMROex experienced 25% loss of time due to software and hardware failure and 10% loss of time due to weather conditions. If the robot builders bring this to the table to the operators, it will not give them any gain in the operations. As explained earlier one of the benefits of robots is that is can work 24/7. This also pose the problem of tether-free robots, regarding the battery range.

4.3 Capabilities of current solutions

One of the areas found to replace human personnel for substantial tasks, is the remote operator. The robots described in chapter 3.5 are solutions directed toward this segment. There have been developed several visions that will contribute to removing human personnel from unwanted tasks. Sprint Robotics identified 5 visions for remote operations. One important fact for remote operated robots is that they should not require extra infrastructure, such as rails. The relevance of the presented robotic solutions in chapter 3.5 towards selected visions is represented in table 1.

Vision	Robotic solution
Operation RO – Monitoring; flat surfaces	MIMROex/Sensabot/Argonauts/DORIS
Operation FA – Monitoring; flat surfaces	MIMROex/Sensabot/Argonauts/DORIS
Operation FA – Monitoring All; all environments (With no infrastructure needed)	Argonauts
Operation RO – Complex tasks	-

Table 1: Remote operated visions for remote operations vs. robotics solutions

The first two visions represent a remote operated (RO) and fully autonomously (FA) operation on flat surfaces, operation in a 2D environment. This vision represents monitoring on the topside, such as sensing gas, infrared (heat), weather conditions, visual and ultrasonic recordings, reading of dials and communicate this to an operator. The third vision represent the same operations as mentioned for the two previous visions, only the operation should be completed in a more complex environment with

stairs and latter's and fully autonomously. Robotics that perform more complex tasks include some lifting and moving through doors is another preferred vision from the industry.

Table 1 conclude that all of the proposed solutions can fulfil the vision for monitoring with movement on flat surfaces. Only the Argonaut is able to perform the required monitoring tasks and move on complex environments. The rest of the robots is in need of some infrastructure. If we look further into the future, a solution to this would be for the robot to build the required infrastructure by itself. Then it could autonomously figure out where it should move and thus be smart. The technology today does exist for smart devices, but for this purpose it is not seen as yet developed. This is also related to the complex environments it should operate in.

The interviews conducted showed that some of the robots are explained more as a development for future research. The potential is present, and in the future, we will see such robots in actions. Unmanned platforms are an area where this is applicable and it will gain the industry. The Argonaut is an already finished product designed for chemical and nuclear environments. I.e. it was already ATEX certified before the development for offshore topsides. This gives it an advantage where the oil and gas industry have been provided with a robot that already works and have been tested. More testing will give a more reliable robot, and it will be seen operating on offshore facilities in 2020.

4.4 Future developments of robotics

In this chapter, we will look further into the expected development of robotics in the domain of topside inspection and monitoring of static equipment. The value chain for this development is important regarding where the push must come from. Further is a look at what the industry sees as the first operations that will be robotized and why.

4.4.1 Robotics value chain

In figure 15 we can see the value chain for robotic inspection and maintenance in the petroleum and (petro)chemical industry developed by Sprint Robotics. Development and design of the robotic systems, procedures and technology comes from the system integrators. The industrial service providers are companies delivering the systems to the end users. The end user is commonly the asset owner or the operator. Knowledge transfer is shown as dotted lines, solid lines denote material transfer. From this value chain, we can characterize where knowledge must come from and which part of the value chain have the power to push robotic technology.
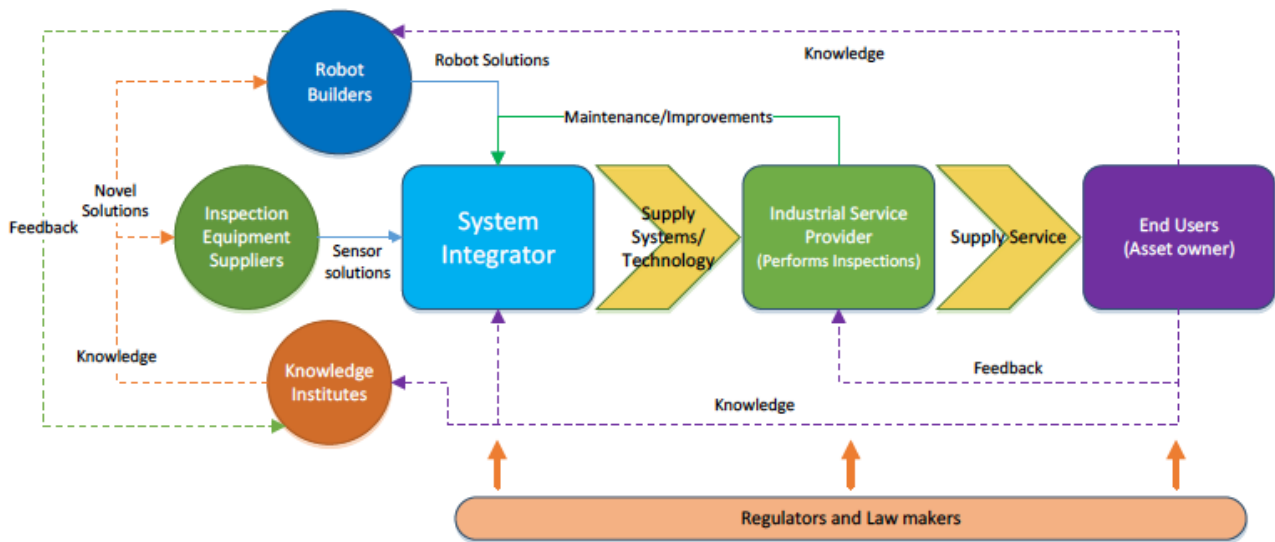
Figure 15: Value chain for robotic inspection and maintenance in the petroleum and (petro)chemical industry (Hoorn et al., 2017)

System integrators builds on the premise from the inspection equipment suppliers and the robot builders, build on the output from knowledge institutes. System providers and the robot builders are often one of the same. This is where the technology is developed in the value chain. It is for the industrial service providers and end users to decide whether to integrate the system or not. Regulators and lawmakers set legal premise behind the use of inspection and maintenance.

So now we have two factors that need to align, the technology readiness and the business readiness. Especially in the O&G industry, often the technology readiness exceeds the business readiness.

In figure 16, the three most important institutions to push robotics in the field of inspection and maintenance is shown.
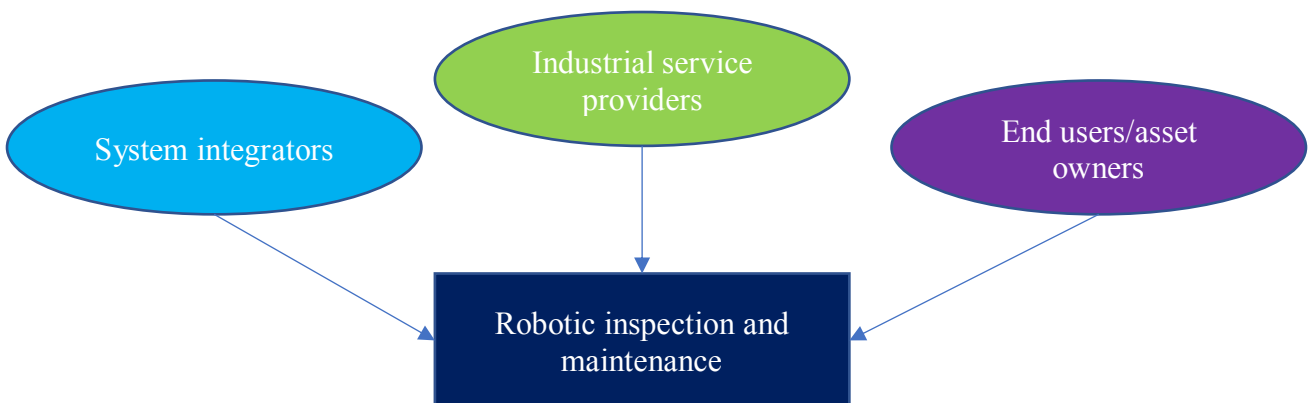

Figure 16: Institutions pushing robotic inspection and maintenance

With experience from the interviews I think there have to be an understanding that you don't find the one solution that can perform all needs. The technology that is being deployed, are to the extent mature enough to be used, but the industry wants more maturity, they want it to be better, more cleaver, want more artificial intelligence and automation. But the reality is that the technologies develop much faster than the industry can be ready for. There will always be a lag there. So essentially what you find in new developments as well, you initially have a scope for a solution. Over time, people get more ideas, but ultimately what you want out of the robot will be more than the robot is developed for. So, you don't find a solution that going to meet all the need at this stage. To give the robot developers the confidence in what they develop can be useful. At the same time, you need to consider this from the O&G industry perspective. More collaboration and insight from the robot developers into the O&G and vice versa is important. To develop the robot technology for operations in complex environments will not be the most efficient if not the design of platform allows robots to work efficient. So essentially, we see that the end users have to a larger degree start to encourage robot developers and give the necessary insight to design and constraints.

A statement from the interviews was that robots will need more space to operate on the topside. This will lead to larger and heavier platforms which increase the cost of the production of the platform. The research shows that this is not necessarily the case. Space is also required for humans and for example for scaffolding. The need of scaffolding is one thing that robots can remove. Essentially the platforms do have to change to some degree, but there exist possibilities that do not require to rebuild entire systems.

Systems comes on skids, and there exist a possibility to design certain skids for robotics. Now the robot's operation area will be more specific and limit the requirements for the robot.

4.4.2 Short term goals for robotics
The short-term goals are connected both to certain tasks the industry will benefit most from and what technology that is available. Safety was found to be the most important driver earlier. If we look towards the subsea industry, we can see a clear connection. Operations under water provide great risk and the industry had to find solutions both for the safety of the divers and because operation at depths that humans not could reach was required. This resulted in the development of remote operated vehicles (ROV´s) and autonomous unmanned vehicles (AUV´s).

Now its apparently time for topsides to also be robotized. We have already seen UAV´s taking over the inspection of flare towers. This remove the need of human personnel climbing up and the industry avoid a huge risk.

Inspection and maintenance was highlighted as the one area that would benefit from robotics. In the interviews, inspection of storage tanks was discovered as the next tasks that will be robotized. This is because of toxic environment inside the storage tanks creates human risk, the storage tanks need to be cleaned for inspection and thus the production need to shut down. The visions for the use of robotics in inspection and maintenance of storage tanks vs. the technology readiness level (TRL), business readiness level (BRL) and the impact the vision will have on the business drivers and plant performance is shown in table 1. TRL and BRL span from 1 (lowest) to 9 (highest) and is a measure of the maturity of the technology and willingness from the business to develop, produce and use the technology. The impact level (IL) span from 1 (lowest) to 5 (highest) and reflects the coverage of the business drivers and the impact the vision will have on these drivers.

Vision for storage tanks	TRL	BRL	IL
Offline autonomous inspection	5	5	2
Offline remote Inspection	6	6	2
Online remote cleaning	3	5	4
Online repair	1	1	4
Online inspection clean tank	1	1	5
Online inspection/uncleaned tank	1	1	3

Table 2: Visions for robotic inspection of storage tanks (Hoorn et al., 2017p. 34)

From table 2 we can clearly see that offline autonomous and remote inspection are closest to be put in action on storage tanks, but it has only a business impact of 2. Online remote cleaning and inspection have a business impact of 4 and online inspection of cleaned tank have a business impact 5, highest possible. This means that keeping the storage tanks online, or in operation have a significant business impact. This have been recognized through interviews as a prioritized area. With the concern of lower oil prices and more focus on efficiency, keeping the plant online will be an essential factor towards the future of development in robotics.

4.4.3 Long term goals for robotics

Robotics is in early stage, especially in the oil and gas industry. In the todays technology advanced world, we would like to think that the sky is the limit. The ideal future platforms would be complete autonomous or semi-autonomous platforms.

Mentioned in chapter 4.2 the remote operator has great potential in robotics. The visions towards this segment is presented in table 3 below.

Vision for remote operation	TRL	BRL	IL
Operation RO – Monitoring; flat surfaces	8	8	3
Operation FA – Monitoring; flat surfaces	6	7	5
Operation RO – Complex tasks	4	5	4
Operation FA – Monitoring; all environments	4	3	3
First responder SA – all environments	4	3	3
Emergency RO/SA – firefighting, evacuate person; staircase	3	4	4
Cleaning SA	5	6	3
Simple maintenance activities	3	3	4

Table 3: Visions for remote operator´s on offshore topside facilities. (Hoorn et al., 2017p. 59)

The impact level for operation that are either remote operated (RO), semi autonomy (SA) or fully autonomous (FA) is on average high. This means that they cover most of the business drivers and have a medium impact. One important driver behind the use of robotics is to put humans out of harm's way.

4.5 Learning from other industries

The O&G industry have come far on the use robotics in subsea operations. Here we can for example see that subsea templates are designed for manipulation with ROV´s. There exist a lot of learning from this inside the industry.

The complex and explosive environments of offshore topsides, have different requirements than other industries. Such as the car industry, which have robotized and automated the production line. If we look to more similar environments, the nuclear power industry has similar requirements. This is clear from the robot from Argonauts which first was developed with this in mind. Another area the O&G industry can look to, is the medical industry. Here the developments of remote medical operations can be adopted in the remote operations on O&G topside facilities.

These industries mentioned above, are just some examples of where the industry can look. The experience gathered from the interviews tends towards that the O&G industry have different sets of requirements considering the complex topsides and the explosive environments compared to industries that have come a long way in this area.

5 Discussion

In this chapter I will discuss theory and the analysis given in previous chapters and the main questions raised in chapter one;

- Does the technology exists to implement automation in condition monitoring and maintenance today?
- What is the most important drivers/incentives behind implementing automation in inspection, maintenance and repair (IMR)?
- What is the overall opinion of automation in maintenance and condition monitoring on offshore topside O&G facilities?
- What is the main barriers for implementing automation?
- Look at the potential cost savings

5.1 Technology and barriers

There are as discussed in both chapter tree and four that the technology as such exist. There are still challenges to convert the technology to the complex and harsh environment and to adapt to today's design based on human processes.

Further the oil and gas industry require very high reliability of systems, it is important that we are able develop simple systems that not contribute to increased complexity. Most systems need a very rigid testing and approval process before it is released for use offshore. A 90% functionality is not good enough. The risk is that we both design for automation and robotics and for human processes. This will increase complexity. Increased number of sensors and instruments may also contribute to increased risk for hydrocarbon leakages.

Today most sensors and instrument offshore are connected to cables. This increase the complexity in design, construction and commissioning. In addition, these sensors and cables may require insulation. Wireless systems are under development and I believe this could be a major contributor to simplification.

Several robots are under development as described in chapter three. These are just some examples but there are a lot of initiatives in the industry. If we look at other industries, it seems like some such as

car manufacturing industry and other manufacturing industries has developed this to a higher level. An example is Borregård that claim they are running most of their factories without direct human interaction but through remote monitoring and operations. I believe that the oil and gas industry should learn from other industries and within the O&G industry, e.g. subsea.

If we look at the O&G industry the focus so far has mainly been on safety issues. We also see that most developments have been on single systems or equipment. Today's design, requirements and regulations are based on human interaction and processes. A stepwise approach seems to be adequate for existing platforms. But several people claim that the big potential for the future is to look at the total topside/platform system. This will require new mindset, technical specifications and requirements need to be revised. We know that Aker has claimed patents for robotized platforms. There seems to be a common understanding that it will take some years before we see such platforms.

The complex and harsh environments and reliability seems to be the main challenge at the time.

The developments with automations and robot technology moves very fast. With the rigid qualification process that might take years it will be very difficult to be able to utilize up to date technology. This is a dilemma but should not stop the development of automation and robots in the O&G industry. Thus, I believe more focus on technology strategy is necessary during early development phase.

5.2 Overall opinion for the potential of automation and robotics

From the interviews and through the literature search it seem to be a common understanding that automation and robot technology has a huge potential. Condition monitoring and maintenance strategy have proved to reduce down time (GE, 2016). Some of the challenges as discussed above is robots and automation in complex and harsh environment.

As said earlier the technology seems to be available but it need to be customized for use offshore. Competence and competence mix are believed to be important. We need to look at how we establish multidiscipline teams. It seems important to connect traditional disciplines with automation and robot competence to be able to identify the potential. Further I believe it is important to connect user, contractors, suppliers and academia. The SPRINT initiative (Hoorn et al., 2017) is one example of collaboration between several stakeholders. We also see that test sites are developed different places.

The question is if the industry need to establish a development program together with contractors, supplier and academia to look both at the strategy moving forward with existing platforms and how to release the potential for future platforms. Regulators and authorities also need to be involved because this may cause changes in regulations and requirements.

Mixed reality is also utilized in several industries and in the oil and gas industry, but mainly related to reservoir and geology applications. Mixed reality (MR) is the combination of augmented reality (AR) and virtual reality (VR)(Kunkel and Soechtig, 2017). This is a very helpful tool for operators that can have VR-goggles that show what and how to inspect or maintain. Further all technical information and work permit will be available. This should be a "low hanging fruit" that should be possible to utilize in the oil and gas industry today both in operation, in design, construction and testing. This will require effective man-machine interphases.

5.3 Potential savings

GE has done a study showing that unplanned shut down is 36% lower with condition based monitoring compared to more reactive strategies. The figure below shows cost of unplanned downtime by maintenance approach.(GE, 2016)
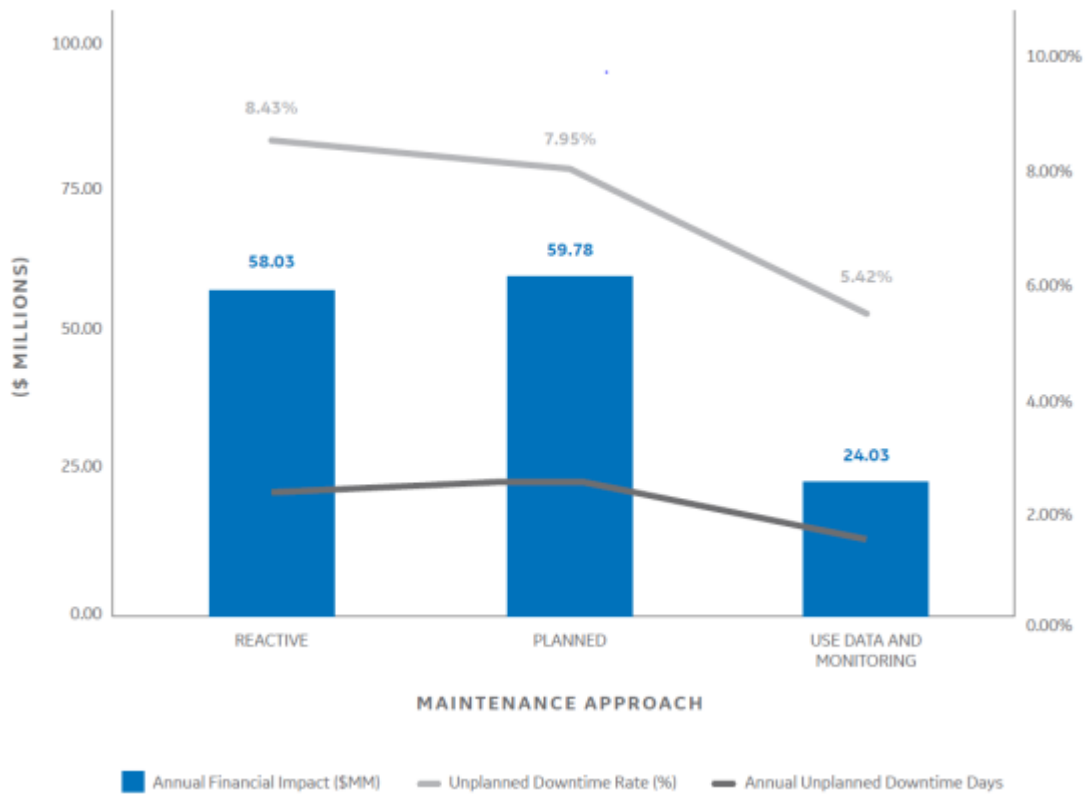
Figure 17: Cost of unplanned downtime by maintenance approach(GE, 2016)

Here we see a huge potential for saving that may add up to hundreds of millions NOK through the lifetime. Oljedirektoratet (2015) show that the operational cost has increased with 16 Billion NOK to 67 Billon NOK per. Year from 2007 until 2014. Maintenance and repair is a major part of the cost. Condition monitoring and robot technology has a big potential for reducing this significantly.

If we look at the expenses during shut down this is shown in figure 19. All the expenses shown in the figure has potential to be reduced by condition monitoring and robot technology.

The calculation need to consider the investment cost and possible added complexity. As discussed earlier it is important that we are able to make the systems simple and reliable and not add complexity by design for both traditional inspection and automation and robot technology.

Repair Costs — 71%
Labor Costs — 40%
Transportation/Logistics — 37%
Equipment/Spares — 14%
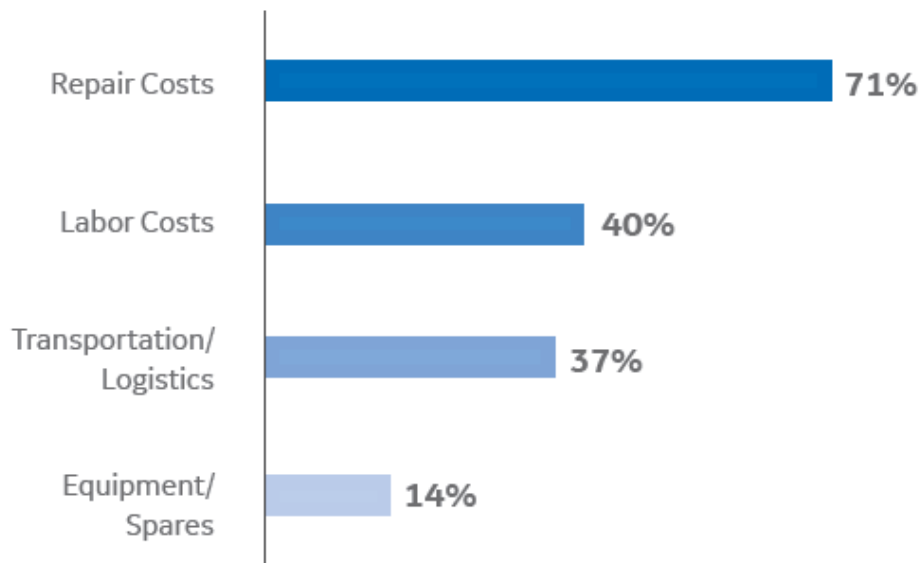
² With a median 27,200 BPD and oil at $50.00 per barrel
³ Assumes 22.5 unplanned downtime days

Figure 18: Major expensive with unplanned downtime(GE, 2016)

If we look at the EMIS app Engie claim that the payback time just for reduced documentation has been less than 6 months.

As said several times there should be a huge potential to implement automation and robot technology. But it is important to ensure control over consequences as complexity, reliability and other indirect elements that can increase risk and cost.

6 Conclusion and proposed further research

6.1 Conclusion

The oil and gas industry has a huge potential to utilize condition monitoring and robot technology. The interviews, the literature, my analysis and discussion confirm this statement.

We are in the initial phase and as seen with all "new" technologies we will at a certain point get a break through. It is difficult to see exactly when that will happen. But we see a very fast development in several industries which means that it will not be too long. It is up to the industry itself and we see that a lot of companies has this topic high on the agenda. I believe the strategy to develop step by step is a sound strategy for the oil industry. Even if it is step by step the speed must increase. A more systematic strategy and collaboration across stakeholders is necessary.

If we look at the robots under developments all seems to have major limitations.

The main obstacle is to adapt to the complex and harsh environment. As said earlier the reliability of monitoring and robot systems is a requirement. One major accident due to the new system will be a major setback for further development.

More focus on technology strategies related to digitalization (including automation and robot technology) during early development of a field is important.

The competence and competence mix is crucial for a sound development. This is important both to be able to identify and develop the potential and to develop reliable and safe systems.

The condition monitoring system are to a certain degree included in new platforms today. One example, the Gina Krog platform is designed for minimum manning. The condition monitoring system is an important tool to achieve this.

6.2 Proposed further research

We see that a lot of the development so far has been performed in different "silos". Further research could look at the potential and criteria for larger collaboration between stakeholders. There exist

possibilities for robots designed for specific tasks, and further research on this topic is needed. To look at it both from the robot developers and from O&G industry perspective.

It could also be interesting to investigate more in detail what other industries are doing and their strategies and what the oil and gas industry can learn from them, as said earlier other industries seems to have reached a higher level.

For future platforms, the possibility and consequences for a fully robotized platform should be investigated. This include consequence for all major stakeholders including regulatory bodies and authorities.

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Appendix A

Interview protocol

Interview objects:

- Anders Røyrøy (Principal Researcher Proc Upstr Automation at Statoil)

- Geir Kaspersen (Control System Engineer at Aker Solutions)

- Rudolf Essel (International Coordinator of Sprint Robotics)

- Pål From (Professor in cybernetic NMBU)

Interview Guide:

1	How do you consider the development of autonomous and remote-controlled robots?
2	What do you consider to be the most important work processes and areas on offshore platforms to be autonomously executed or executed remote by robots today?
3	What do you see as the most important drivers for automation and robotics in the O&G industry?
4	Is this a prioritized area of development in the oil and gas industry today, from your perspective?
5	What do you see as the main barriers for implementing robots on platforms today?
6	What do you consider as the long-term goal regarding robots in inspection and maintenance on topside offshore facilities?
7	What is your opinion on the potential of cost reduction in the O&G industry from implementing robots?
8	Which tasks, regarding inspection and maintenance, do you believe the industry are closest too, to implement robotics?
9	Does it exist solutions today that can be useful for the O&G industry?
10	Do you consider any other industries that the O&G industry can learn from?