Master's thesis

NTNU
Norwegian University of Science and Technology
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Department of Engineering Cybernetics

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Design Implications for Robotized Testing and Inspection of Fire and Gas Detectors

Master's thesis in Industrial Cybernetics
Supervisor: Mary Ann Lundteigen
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Abstract

The oil and gas industry has experienced a substantial increase in automated machinery and utilisation of process safety systems in the later years. The next frontier is the utilization of unmanned facilities, a cost-effective alternative to subsea production systems, offering similar functionality and robustness. Robotics can be used to take on high-risk maintenance activities on an unmanned facility, limiting safety concerns regarding human operators.

This thesis will map detectors feasible for fire & gas (F&G) detection, and investigate how choice of detectors, installation, layout and requirements and regulations affects the choice of a robotic solution. Possibilities for unmanned offshore topside platforms are reviewed. Further, sensor selection and robotic design, including cases regarding robotic F&G detection procedures, are presented and discussed.

It was granted access to a company test procedure concerning F&G detection with the objective of changing an inspection procedure from human to robotic intervention. Further, design implication connected to the study cases are discussed, culminating in a choice of which robotic design solution has the most potential for F&G detection on an unmanned facility.

It was concluded with an appropriate robotic solutions, adequately performing assigned testing, inspection and maintenance tasks on an unmanned facility. The robotic design has been chosen based on prerequisites to be able to perform autonomous F&G detection on unmanned facilities.

Sammendrag

Olje og gassindustrien har erfart en økende trend innenfor automatisert maskineri og bruk av prosessikre systemer de seneste årene. Den neste grensen er å bruke ubemannede innretninger, et kosteffektivt alternativ til produksjonssystemer på havbunnen, som tilbyr lignende funksjonalitet og robusthet. Robotikk kan benyttes til høy-risiko vedlikeholdsaktiviteter på ubemannede innretninger, som begrenser sikkerthetsbekymringer angående menneskelige operatører.

Denne masteroppgaven vil kartlegge relevante brann og gass (B&G) detektorer, og undersøke hvordan valg av detektorer, installasjoner, oppsett og krav påvirker valg av robotløsning. Det er videre gjennomgått muligheter for ubemanned fasiliteter topside. Videre har det blitt sett på valg av sensorer og robotdesign, inkludert en diskusjon rundt caser angående B&G deteksjonsprosedyrer, gjennomført av en robot.

Det ble tildelt tilgang til et selskaps test prosedyrer angående B&G detection. Målet var å endre prosedyrene fra menneskestyrt til robotstyrt. Videre ble designimplikasjoner tilknyttet casene diskutert. Dette førte til valg av hvilket robotdesign som har mest potensiale for B&G deteksjon på en ubemannet innrettning.

Det ble konkludert med en passende løsning for robot, som kunne utføre testing, inspeksjon og vedlikeholds-oppgaver på en ubemannet innrettning. Robotdesignet har blitt valgt basert på forutsetninger for å være i stand til å utføre automatiske B&G deteksjoner på en ubemannet innrettning.

Preface

This is a Master's thesis conducted as part of the study program Industrial Cybernetics at NTNU. The project was accomplished during the spring semester of 2020. This project was started by SUBPRO, on request from Equinor, to analyze the possibilities of autonomous robotized inspection and monitoring on unmanned topside facilities. Equinor has put their personnel and assets available for guidance and testing.

Acknowledgement

I would like to thank Mary Ann Lundteigen, my supervisor from NTNU and SUBPRO connection, for all the excellent guidance and pleasant conversations.

I would also thank Erling Lunde and Gunleiv Skofteland from Equinor for their assistance and effort facilitating this master thesis.

Trondheim, 2019-07-06

Christoffer Grytøyr

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Abbreviations

API	=	American Petroleum Institute
CCTV	=	Closed Circuit Television
DOF	=	Degrees Of Freedom
EDP	=	Emergency Depressurization
E/E/PE	=	Electrical/Electronic/Programmable Electronic
ESD	=	Emergency Shutdown
EX	=	Explosion
FRB	=	Fast Rescue Boat
HSE	=	Health, Safety and Environment
HVAC	=	Heating, Ventilation and Air Conditioning
IR	=	Infrared
ISC	=	Ignition Source Control
LEL	=	Lower Explosion Limit
O&M	=	Operations and Maintenance
OSR	=	Offshore Service Rig
PFD	=	Probability of Failure on Demand
PSA	=	Petroleum Safety Authority
RBI	=	Risk Based Inspection
RCM	=	Reliability Centered Maintenance
SCADA	=	Supervisory Control And Data Acquisition
SIF	=	Safety Instrumented Function
SIL	=	Safety Integrity Level
SIS	=	Safety Instrumented System
UEL	=	Upper Explosion Limit
UV	=	Ultraviolet
W2W	=	Walk-To-Work

Chapter 1

Introduction

This chapter presents the background and main objectives for the thesis. Further, the approach used is detailed in section 1.3, while limitations surrounding the thesis is outlined in section 1.4. Finally, the chapter gives an overview of the remaining thesis structure.

1.1 Background

The oil and gas (O&G) industry has experienced a substantial increase in automated machinery and utilisation of process safety systems in recent years. This trend will continue, and rapidly grow as the industry evolves through its next phase, Industry 4.0. Industry 4.0 will increase automation and process safety data exchange through the use of AI, robotics, cloud storage and big data analysis. The next big step for the O&G industry is combining this technology with safety, environmental and economical improvement.

Transportation and training of personnel, and infrastructure required for manned platforms are bottlenecks, making the possibilities for unmanned platforms desirable. This is backed up by health and safety considerations, where the exclusion of manning could result in less possible risks and injuries. Unmanned concepts can make discoveries near existing infrastructure more profitable, extending field operation and activity level. The main driver is to make unmanned facilities a cost-effective alternative to subsea production systems, offering similar functionality and robustness.

Robots can be used to take on high-risk maintenance activities, and other activities that are dangerous or difficult for human workers. Maintenance workers in industrial environments can thus reduce their exposure to dangerous situations or environments. The monitoring capability of a robot is similar or better in comparison to the capacity of humans, and favourable compared to fixed installed cameras. Moreover, a fixed setup is often useless in case of a major incident due to lost communication or damaged equipment. Automated surveillance of an unmanned platform by a mobile robot has high potential of improving the speed and quality of decision making, while reducing operating expenses and risk of unmanned operation of the platforms.

A mobile robotic system can detect issues earlier due to more frequent visits compared to manned inspection routines. Using a robot as first responder on emergencies might be useful as it takes time to mobilize ships in case of a failure. It would also be useful, in case of a shutdown, to send out a robot with a camera to do the first inspection and localize a leakage or similar. The robot can detect leakages, hot spots, gas leaks, and deteriorating machines before a major problem occurs due to the high accuracy and repeatability of its measurements.

The master thesis pre-study [1] listed that:

- Studies on design for facilitating autonomous robotic inspection. I.e. accessibility and standardized equipment.
- Studies into which EX equipment will be necessary on an unmanned platform, as well as EX proofing of robots and EX certification.

are possible tasks in need of more insight. One of the interview subjects in the pre-study stated that half of the maintenance hours goes to scheduled maintenance. Almost all of this on explosion (EX) control, testing of safety functions and certifications.

Fire and explosions are the most serious unpredictable issues affecting life and business losses. The real cause of most incidents is what is considered human error. As fire and explosion protection affects all other elements of the design of a project, it becomes the prime starting and focal point in the initial proposals, layout, and process arrangements.

1.2 Objective

In the future, the goal is to implement autonomous robots for inspection and maintenance on offshore topside facilities. Initially, this will most likely revolve assisting human inspections and visual inspections and/or light maintenance work. This thesis aims to show that autonomous mobile robotics are ready to inspect and detect fire or gas leakages, as well as monitor and test fire & gas (F&G) Systems, with a possibility to expand to more thorough maintenance work in the future.

This thesis will map which detectors that are feasible to use for F&G detection, and investigate how choice of detectors, installation, layout and requirements and regulations affects the choice of a robotic solution. There will be a weighted focus on gas detection. Sensor selection and robotic design will be discussed, and cases regarding robotic F&G detection operations will be presented and deliberated. The thesis aims to review possibilities for unmanned offshore topside platforms. Furthermore, it will create insight into how some solutions could be designed differently to facilitate better for robotized inspection and maintenance of F&G detectors. Also, how requirements and regulations for F&G change when the platform is unmanned.

Further, the objective is to find out if a provided maintenance scheme is possible to change, to facilitate an autonomous robotic approach on unmanned platforms. The main focus is on detection of fire and gas, which will be crucial to detect early to remain operational. Main questions for this topic are which design criteria is necessary to facilitate this change, and which tasks disappear or differ as a result of this implementation on unmanned facilities.

1.3 Approach

In broader terms, a large literature study was conducted to cover all angles of the thesis objective. Additionally, conversations and meetings with industry personnel and sparring with the appointed NTNU supervisor was organized when needed.

A lot of the scope surroundings and a draft scope were made in January with assistance from external and internal supervisors. A fixed scope was not set when the work begun, making the focus in the beginning finding possibilities surrounding F&G detection. Further developing into studies into unmanned facilities, as it was a prerequisite. The scope was further developed along the way with help from the internal supervisor.

Firstly, a deep dive into detection techniques for fire and gas seemed vital to understand what can be used on a robotic system for reliable detection. Every detector technique deemed relevant has been searched for and presented in chapter two. To understand the material surrounding fire and gas detectors, some terminology repeatedly used in source material was found necessary to present before review of the detectors.

Vital to the task, a study into which robotic technologies that are available for testing, inspection and maintenance in the O&G industry were conducted. As other industries might have significant progress in the area the last years, it was not limited to just this industry. The robotics should be preferably autonomous, or remotely controlled to fit the scope of unmanned facilities. Robots controlled on-site were considered if the design showed promise, such that changes could lead to autonomy or remote control. This was done to figure out which type of concept is most likely to prevail when employed with inspection and testing tasks without human supervision. Which tech is most robust, is easier to develop autonomy for, and has the best facilities for detection equipment.

Initially, a simulation of a robot performing a given task, was supposed to be a proof of concept. As this had to be abandoned, further explained in section 1.4, a new approach was needed. Subsequently, emphasis was put on finding good literary sources and a great deal of analysis around thesis questions, as well as using the pre-study to a greater extent. Some information on maintenance and testing procedures acquired from a SUBPRO partner became the main focus for the problem formulation in chapter 4. The new method became to conclude on design implications based on literature, information from industry personnel, own experience and the case study in chapter 4.

1.4 Limitations

The thesis has a qualitative and in-depth approach using some key personnel involved in development of inspection and maintenance strategies and solutions. There was not performed any quantitative study, questionnaire or interactions with other personnel outside of SUBPRO partners.

There is not a main focus on how the robot should move or how the robot should communicate with computers and control systems. Therefore, demonstrating possible applications through the development of software was not a focus point. However, when these matters are relatable for choice of detectors, placement or detection ability, the themes might be subject to discussion. Design implications, as in the thesis title, is in this context related to requirements and implications concerning performance of operations.

The testing procedure offered by one of the SUBPRO partners are confidential and not open for public use. The document has been anonymized to avoid detection or outing of any individual or industrial partner. The plan has been shorted down at the writers discretion, to include relevant points for the thesis and to avoid potential recognition. The data of this document is from a manned platform, as no existing data from an unmanned facility inspection and maintenance were available.

Due to the unprecedented situation surrounding the COVID-19 pandemic, the simulation experiment for validation of using Gazebo and ROS had to be abandoned. The school closing, and no access to necessary computing equipment, made the validation experiment postponed indefinitely. These changes has lead to a more theoretical approach. As much time was used to prepare the simulation, the process are briefly explained in section 4.4. There was also a plan to go through incidental history regarding F&G systems from one of the SUBPRO partners. However, due to the lockdown, it was not possible to access the company's systems.

1.5 Outline

The thesis begins with two literature study chapters. Chapter two presents researched F&G detection techniques, as well as technical requirements related to F&G detection. Incidents or conditions on facilities in dispute with presented requirements are reviewed. Chapter three explores industrial use of mobile robotics and unmanned facility design. It contains the advancements done over the years for this particular field, with a focus on some of the newer robotic solutions.

Chapter four presents a case regarding possible tasks for an autonomous robot to acquire from human workers for use on unmanned facilities. Chapter five combines the research and case study results to present robotic solutions that are deemed viable to perform set assignments. It also contains a discussion on the main topics and analysis of relevant design aspects. This is followed by chapter 6, concluding the project including recommendations for further work.

Chapter 2

Fire & Gas detection techniques and requirements

This chapter aims to build a basic understanding of terminologies and technologies related to safety instrumented systems (SIS) in section 2.1. Further, one of the SIS; the fire & gas (F&G) detection system, are especially focused, as well as a walk-through of relevant detection technologies available. This thesis chapter also focuses on standard requirements related to F&G detection. Lastly, incidents or conditions on facilities in dispute with presented requirements are reviewed.

2.1 Safety instrumented systems terminology

In this section, some basic terminology and concepts will be explained. This is the foundation for understanding SIS as i.e. F&G systems.

2.1.1 Safety integrity level

IEC 61511 [2] phrase that SIF are protective functions implemented in a SIS. A typical SIS is comprised by multiple SIFs; typically each SIF has process sensors that measure a process deviation, a logic solver that executes the functional logic, and final control elements that brings the process to a safe state. IEC 61511 addresses SIS based on the use of electrical, electronic, or programmable electronic (E/E/PE) technology in the process industry sector.

DNV GL defines safety integrity as “The probability of a Safety Instrumented Function (SIF) satisfactorily performing the required safety functions under all stated conditions within a stated period of time” [3]. In other terms: What is the probability of the safety function working correctly whenever needed. IEC 61511 [4] defines Safety Integrity Level (SIL) as a discrete level allocated to the SIF for specifying the safety integrity requirements to be achieved by the SIS.

Deciding SIL demands is often referred to as SIL allocation or SIL targeting. SIL allocation means deciding SIL demands for the whole safety function, from sensors to activated equipment. It can also include breaking down the SIL demand to revolve around subsystems and components. The step prior to allocation is the risk analysis. The risk analysis should reveal the probabilities and consequences of any possible failures.

One method for SIL allocation is using a risk graph. The risk graph dictates SIL demands from a step by step evaluation of the scope of risk the safety function should attend to [5]. Both IEC 61508 and IEC 61511 advocate a risk-based approach for setting the performance levels of safety instrumented functions by assigning a safety integrity level. The SIL demand that emerges from the risk graph must contribute with enough risk reduction according to risk acceptance criteria. This is called calibration, and is only done once [5].

There are four possible levels, where SIL 4 is the highest level of safety integrity and SIL 1 is the lowest. SIL 4 is not recommended. There are three basic categories associated with this measure: Hardware safety integrity, software safety integrity and systematic safety integrity.

Hardware safety integrity is based upon random hardware failures, and can be estimated with reasonable accuracy via probability of failure on demand (PFD). Software safety integrity is a part of the safety integrity of a safety-related system relating to systematic failures in a dangerous mode of failure that are attributable to software [6]. Systematic integrity is harder to quantify as it revolves a diverse range of failures, i.e. failures during specification, design, implementation and operations. This may affect both hardware and software. Requirements from all three categories must be fulfilled (at the level assigned by SIL) in order to claim a SIL level.

Factors to consider when allocating are:

- How often does an incident occur where the SIF needs to take action?
- What is the most severe consequence without SIF?
- How exposed are personnel or environment for injuries?
- If personnel or environment is exposed, how can the severity of injuries be reduced?

PFD means the average failure probability of a safety function due to dangerous failures. The average PFD is calculated for a period corresponding to regular proof test interval τ. Table 2.1 shows how SIL level is allocated based on calculated PFD.

Table 2.1: PFD specifying a required SIL for each Safety Instrumented Function [7]

Safety Integrity Level	Probability of Failure on Demand	Risk Reduction Factor
SIL 4	$10^{-5} \geq$ PFD $< 10^{-4}$	100,000 to 10,000
SIL 3	$10^{-4} \geq$ PFD $< 10^{-3}$	10,000 to 1000
SIL 2	$10^{-3} \geq$ PFD $< 10^{-2}$	1000 to 100
SIL 1	$10^{-2} \geq$ PFD $< 10^{-1}$	100 to 10

2.1.2 Voting

Redundancy is the presence of more than one element to carry out the same function, and is an important means to improve the reliability of SIS. It provides fault tolerance and increases the reliability, but also adds complexity.

Voting specifies the impact of redundancy on the fault tolerance. A mooN voted structure is a structure of elements that is functioning when m-out-of-N channels are functioning, and which fails when (n-m+1) or more of its elements fail [8].

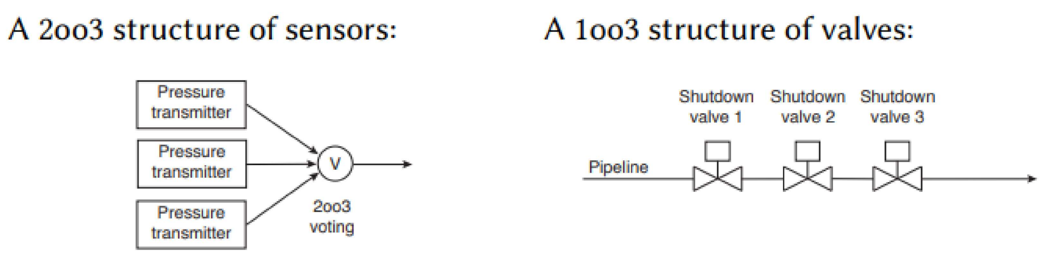


Figure 2.1: Voting graphically exemplified [8].

As can be seen from figure 2.1, a 1oo3 structure can be viewed as a series circuit where if one sensor gives an alarm, it is enough for the whole system. A 2oo3 system shown to the left is more similar to a parallel circuit, where 2 of the 3 transmitters needs to alarm for the system to shut down.

The mooN voting strategy would prevent a false alarm caused by a single spurious source or electronic failure of a single component [9]. This strategy is widely used in safety systems, such as F&G, to ensure high reliability meanwhile low false alarm. However, even in the case of voting, there is still a chance of detecting minor leaks in place of a major leak, which results in false actions and consequent costly trips to facilities. A common solution to address this issue in the industry, is using a voting strategy with different detection levels, which reduces the chance of a false detection [10].

Nicol [11] also sites that redundant detectors are sometimes deployed in remote facilities in order to reduce the potential for false alarms. The idea is to implement a voting system involving multiple detectors. When this configuration is employed, one fire alarm signal triggers notification of a potential threat, and two or more alarm signals trigger executive actions, such as equipment shutdown and/or suppression.

2.1.3 Barrier management

Petroleum Safety Authority Norway's (PSA) note on barriers [12] explains needed information on barriers and how to manage them. Barriers are explained as measures to protect facilities, environment or personnel in dangerous failure or accidental situations. The functional integrity is upheld by either technical, organizational or operational barrier elements. Barrier management means to systematically and continuously ensure that necessary barriers are identified and protecting from failure or other dangerous incidents.

According to PSA management regulation §5, barriers should discover events, stop development of events and limit damage [13]. Barrier elements should have high functionality, integrity and robustness. This implies the impact barriers have on events, how they manage to stay intact at all times, how they deal with unorthodox situations and if they survive a possible event. The management regulations §§4-5 states that as a basic principle, probability-reducing measures should be prioritized above consequence-reducing measures, although there is often a need for both.

It is common to split into passive and active barriers. Passive barriers are present without activation or intervention i.e. a firewall. Active barriers demand activation or intervention. Passive barriers should commonly be preferred over active barriers. If active barriers are chosen, automatically activated barriers are preferred. This leads to the preference of technical barrier elements ahead of elements in need of human intervention. The technical elements such as reliability, strengths and weaknesses when handling incidents and serious accidents, should be compared to organizational and operational elements [12]. Active and passive barriers are important factors in F&G systems.

ISO 13702 defines active fire protection as equipment, systems and methods which, following initiation, can be used to control, mitigate and extinguish fires [14]. One example of an active fire barrier is a deluge system. This is a system to apply fire-water through an array of open spray nozzles by operation of a valve on the inlet of the system. Passive fire protection could be coating or cladding, or a free-standing system providing thermal protection to restrict the rate at which heat is transmitted to the object or area being protected.

2.2 Gas detectors

In this section, flammability limit is explained, as well as the different gas detector technologies. Gas detectors are often grouped as either point or line gas detectors, and after which principal of detection is used, i.e. catalytic, optical or acoustic. Gas detectors can also use either wired communication and power supply, or wireless communication and batteries.

A point gas detector comprises of a unit that measures gas concentration around one point. It is based on the fact that the target gas must be in physical contact with the detector, while covering a limited area. To obtain reasonable coverage, several point detectors has to be installed in the area.

A line gas detector is also called an open path detector. The detector measures gas concentration in a beam and is split in a transmitter and a receiver with a distance of 0.5-200 meters. The concentration of the target gas passing along the beam path is measured instead of a given point. This way, a large area can be monitored, replacing several point detectors. On the other hand, a loss of one open path system (i.e. obstruction of beam path by equipment or personnel) might leave a facility more vulnerable.

2.2.1 Flammability limit - LEL/UEL

There is only a limited zone of gas/air concentration which will produce a combustible mixture. This zone is specific for each gas and vapour and is bounded by an upper level, known as the Upper Explosive Limit (UEL) and a lower level, known as the Lower Explosive Limit (LEL).

IEC 60079 defines LEL as the concentration of flammable gas or vapour in air, below which an explosive gas atmosphere does not form [15]. UEL is the concentration of a flammable gas or vapour in air, above which an explosive gas atmosphere does not form. In this standard, Lower Flammable Limit (LFL) and LEL, and Upper Flammable Limit (UFL) and UEL, are deemed synonymous. This thesis will continue the use of LEL and UEL. Above UEL, the mixture is almost pure gas, meaning there is no oxygen and no combustion possible as the air is too rich. Below LEL, the mixture is almost pure air, meaning there is insufficient gas and no combustion possible, as the air is too lean. The flammable range therefore falls between the limits of the LEL and UEL for each individual gas or mixture of gases, as shown in figure 2.2.

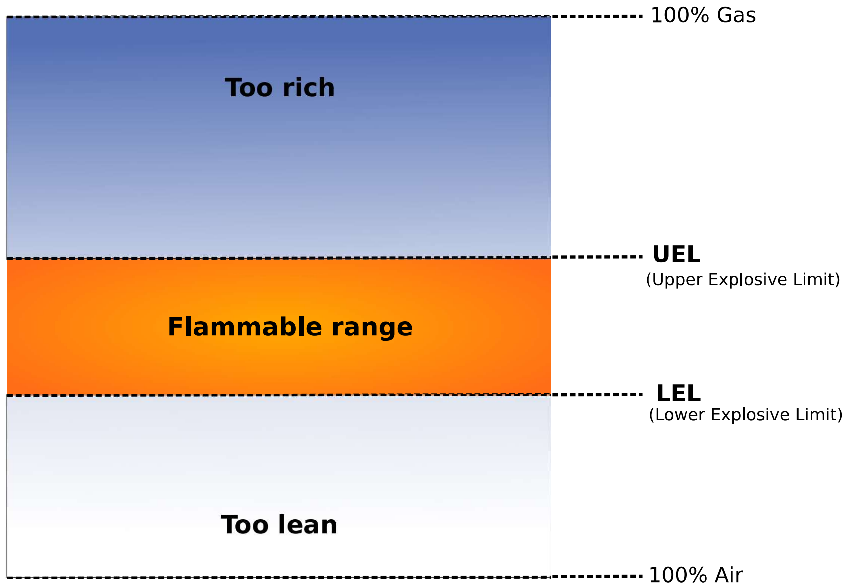


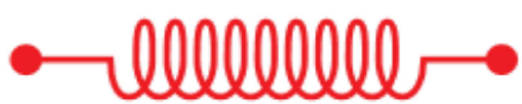
Figure 2.2: The flammable range with UEL and LEL points adapted from [16].

In offshore installations, the aim is to avoid the leaked gas from reaching its flammable limit. Detector systems are set up to detect gases from 0% to 100% LEL, as combustion occurs between LEL and UEL. If LEL is reached, shutdown or emergency procedures takes place, Honeywell sites that procedures should commence at 50% LEL to provide an adequate safety margin [16].

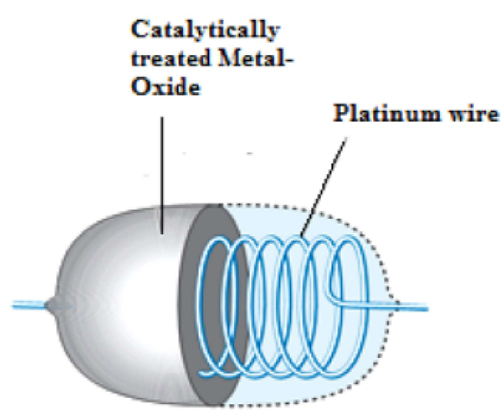
2.2.2 Catalytic gas detectors

A catalytic gas detector is a point gas detector detecting flammable gases by heat measuring of catalytic oxidation. The flammable gas reacts with oxygen by means of a catalyst, usually of a noble material such as Platinum. The reaction creates heat, and the temperature rise is identified by the detector [17]. This type of detector needs to be calibrated regularly, every four months or more frequently, and has a longer response time than i.e. optical detectors. There is no self diagnostics, meaning there is no warning if the detector is deteriorating or malfunctioning [18].

The catalytic gas sensor was originally a coiled Platinum wire. Alone, it is a poor catalyst, needing a temperature of 900-1000 °C for detecting hydrocarbon gases. This is also close to the temperature Platinum starts to evaporate. The solution to this problem was to coat the Platinum with other metal oxides and treat the sensor with a catalyst like i.e. Platinum [19]. Both approaches are shown in figure 2.3.



(a)



(b)

Figure 2.3: (a) Coiled Platinum wire as an early catalytic gas sensor [20].
(b) Catalytic bead sensor with metal oxide coating [20].

Catalytic detectors are robust, simple to operate and easy to install and calibrate to specific gases. They are long lived with a low life-cycle cost and flexible with application. On the other hand, catalysts can become poisoned or inactive due to contamination. Prolonged exposure to high concentrations of combustible gas may degrade sensor performance.

Microhotplates is an alternative to the Platinum coil due to lower power consumption. This type of sensor contains a catalytic surface coated on a hot plate with a Platinum resistor that heats up the catalyst to a high temperature where any flammable gas molecules can ignite. The concentrations of gases can be detected by monitoring resistance change of the Platinum resistance because of increase in temperature [21]. An image of the microhotplate is shown in figure 2.4.

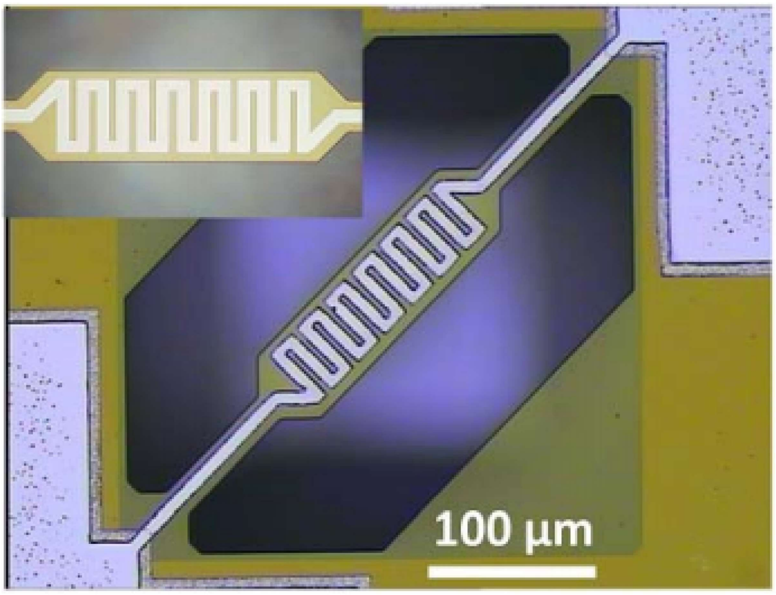


Figure 2.4: Optical photo of the microhotplate [21]

2.2.3 Electrochemical

Electrochemical detectors works like a transducer converting gas concentration to an electrical current. The detector is made up of a sensing-, counter- and reference electrode sealed in a container with electrolytes. The detected gas reacts with the sensing electrodes, generating electrical current proportional to the amount available in the environment. Electrochemical detectors respond quickly to a variety of gases, including carbon monoxide, hydrogen sulfide, and hydrogen chloride, and are highly accurate.

The electrodes act as a catalyst for the electrochemical reaction while remaining unaffected by the conversion of gas molecules into other species. The speed of the reaction decreases parallel with temperature, yielding a narrower temperature range than of other types of detectors. Electrochemical cells have a limited pressure working range - pressures outside of 10% of atmospeheric pressure affects the accuracy of gas measurement [22]. Over time, the electrodes can be affected by small impurities, degrading its sensing ability. Combined, these issues make electrochemical detectors sub-optimal for harsh environments such as the arctic.

2.2.4 Acoustic/Ultrasonic detectors

Acoustic gas detectors are point gas detectors measuring ultrasonic noise (25000-100 000 Hz) inaudible for human ears, generated by gas leakages in pressurized systems. The range for this type is between 10 and 20 meters dependent on the size of the leakage, gas pressure and ultrasonic background noise. Acoustic detectors can measure leakages independent of gas dispersion, gas spread and wind direction. They can identify small gas leakages, down to 0.1 kg/s, giving a potential for early warnings before escalation. Acoustic detectors include self diagnostics and provides a current signal between 0-20mA with a 4-20mA measuring range for gas [18].

Acoustic detectors works well in gas facilities with dry gas. It is not recommended for facilities with liquid or multiphase leakages, as this type of emission demands very low background noise for the detector to function optimally [18]. Unlike other detectors which measures gas concentration in %LEL or ppm, acoustic detectors measures gas leaks in sound pressure level (SPL), thus a higher leak rate gives a higher SPL discharged by the emitted gas [22].

This detector system gives instant detection of pressurized gas leaks and is impervious to changes in wind direction or gas dilution. Ultrasonic detection applies to all types of gas, making it quite versatile on many applications. Another advantage is that their performance can be verified with live gas leaks during commissioning. Using an inert gas, operators can execute simulations of gas emissions with a known leak rate and test detector response in potential locations. Acoustic detectors are, however, unable to detect low pressure leaks that are not within the ultrasonic frequency range, meaning leaks outsides ultrasonic coverage remain undetected.

2.2.5 IR gas detectors

An IR gas detector could be both a point gas detector or line gas detector. It identifies hydrocarbon gases by sending infrared beams with two distinctive wavelengths (measuring- and reference wavelengths) from a transmitter to a receiver. The measuring wavelength coincides with the vibrations of the molecules in the gas, making the gas absorb light with this wavelength [18].

An IR detector can not calculate gas concentration and size of the gas cloud covering the IR beam. During calibration, gas cells with known concentration and volume are used to store different levels of IR absorption in the receiver database, letting the gas detector be able to measure LEL. Optical gas detectors are usually tested once every year, but has a high degree of self diagnostics.

The light intensity in the IR beam hitting the receiver is converted to electrical current between 0 and 20 mA. The measuring range for gas is 4-20 mA, indicating detection of gas from 0% to 100% LEL, while lower and higher currents are committed to fault alarms. Open path IR detectors use % LEL per meter (LEL_m) as opposed to point IR detectors using % LEL.

IR detectors are immune to chemical poisoning, are not dependent of oxygen or air to detect gas, and offer a “fail-to safe” technology since optical sensing is an active technology. Meaning, sensor fault or failure is continuously monitored, conveying information to the user [23]. IR detectors are factory calibrated and are virtually maintenance free, making them a viable option where detectors must be located in inaccessible areas. Maintenance is limited to periodic cleaning of the optical windows to help ensure dependable performance [24].

Detection principle

Most substances will absorb parts of electromagnetic radiation when exposed. Which wavelengths absorbed depends on the substance. On the Norwegian Continental Shelf (NCS), hydrocarbons are mostly methane. As can be seen from figure 2.5, Methane absorbs a lot of energy from an IR beam with wavelength 3,3 μm, but little energy from an IR beam with a wavelength of 3,1 μm [25].

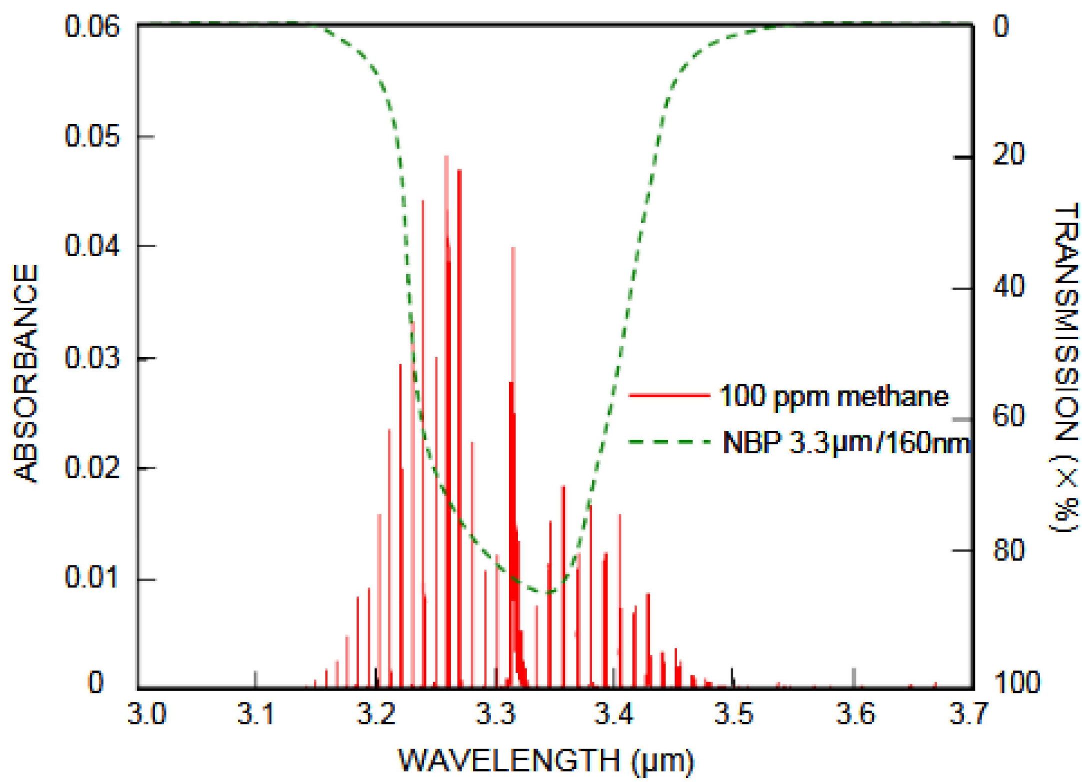


Figure 2.5: Simulation of methane absorption spectrum near 3.3 μm and transmission spectrum of the bandpass filter [25].

To detect gas and compensate for effects from fog, humidity and other environmental impacts, the IR beams measuring wavelength and reference wavelength are compared. The difference between them when hitting the receiver is a target for gas concentration (i.e. % LEL methane).

Håbrekke & Onshus [18] has made a sketch showing the principle for an IR point gas detector, shown in figure 2.6. The sketch has two IR sources, each with an optic filter, transmitting one beam with the measuring wavelength and one beam with the reference wavelength. The beam is transmitted through a lens and reflected back by a mirror. Both beams are split by a beam splitter to measure respectively gas concentration in the air, and possible changes in the IR source, optics or measuring sensor.

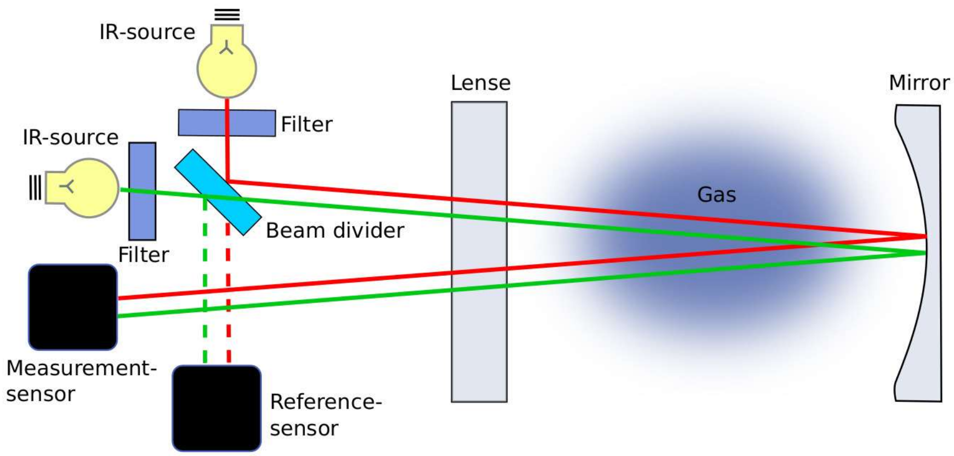


Figure 2.6: Measuring principle for an IR point gas detector adapted from [18].

The philosophy for open path IR detector is the same as for IR point detectors, but with a considerable distance between the light source and the detector, meaning length is not fixed. General monitors [23] provides a graphic representation of the open path IR detection method, which has been adapted and is shown in figure 2.7.

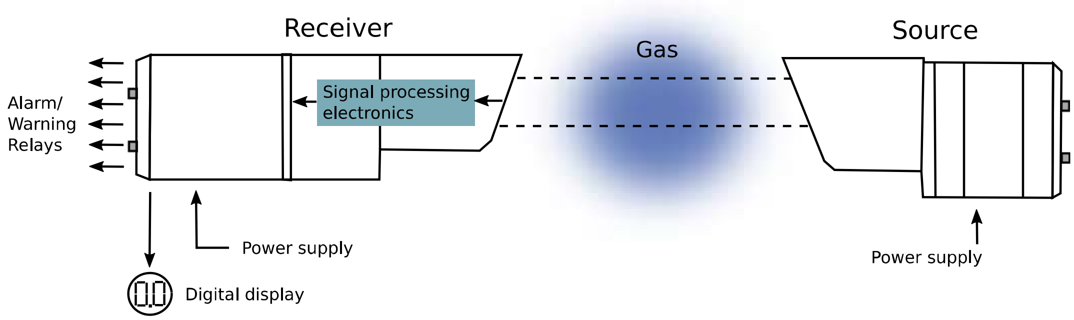


Figure 2.7: The open path system for IR detectors adapted from [23].

2.2.6 Optical gas detectors

Optical gas detectors are based on the principle of absorption of spectrometry. Spectrometry is the measurement of the interactions between light and matter, and the reactions and measurements of radiation intensity and wavelength. Sensors using this technology are quite expensive but have great sensitivity and reliability compared to other gas detectors. IR optical sensing is the most widely used technique for optical gas detectors. The detector has a fast response time, and is not affected by chemical inhibition such as the catalytic detector. The detectors are well suited for harsh environments, such as a desert or the arctic [23].

Laser detectors

Laser detectors are a type of optical line gas detector. This type is robust against external weather conditions, yielding few fault alarms compared to traditional IR line gas detectors. A laser detector has good self diagnostics, quick response and high sensitivity, meaning it can detect low gas concentrations. The laser detector usually measures one specific - or a few specific gases, meaning once calibrated, it does not respond to other hydrocarbon gases. This is a trait that may both be an advantage and a disadvantage dependent on the situation. On the advantageous side, many false alarms and unexpected alarms from other gases are avoided, as well as knowing which gas is detected. In an area exposed to several types of gas, the calibrated gas is the only one detectable. Other gases will neither give a gas alarm nor false alarm, making it a disadvantage for this type of detector.

2.3 Flame Detectors

To prevent catastrophic events such as a fire, proper flame detection should be installed. To select correct equipment, it is vital to gain an understanding of the principles of flame detection and available detection technology. Most flame detectors use optical methods like ultraviolet (UV), infrared (IR) and visual flame imaging. IR and UV radiation are emitted in a combustion, letting flame detectors detect UV and IR light at specific wavelengths. General monitors' overview of how to choose a flame detector [26] and Nolan's handbook on F&G detection [9] are used as sources for the various flame detectors.

2.3.1 Optical flame detectors

Using an UV or IR range, optical fire detectors observe for flames, alarming if detected. These detectors might be equipped with a time delay to eliminate false alarms. Commonly used optical detectors include UV, single and dual frequency infrared (IR, IR/IR) and combinations of ultraviolet and infrared (UV/IR). There is no performance standard for flame detectors [9], meaning that technical specifications need to be analyzed to conclude with the right type of detector.

Ultraviolet flame detectors

The UV flame detector responds to radiation in the spectral range of 180-260 nm. The UV detector has good sensitivity at short ranges (0-15m) [26]. At longer distances, UV waves might be absorbed by air, smoke, dust or other organic materials, affecting detection ability. They can also be affected by arc welding, halogen lamps and lightning, thus being used mostly inside [26].

UV/IR - Dual UV/IR

When a UV optical sensor is integrated with an IR sensor, a dual band detector is created, which is sensitive to the UV and IR radiation emitted by a flame. The combined UV/IR flame detector offers increased immunity over the UV detector. This detector operates at moderate response speeds, and is suited for both indoor and outdoor use. Similarly to UV detectors, the detection range of these instruments may be reduced by i.e. heavy smoke.

As flames emit IR radiation it can be recognized by using IR technology. Other sources of IR radiation that might disturb detection are i.e. hot surfaces, halogen lamps and the sun, potentially leading to false alarms. With both UR and IR technology implemented, the system is still prone to false alarms as it effect both channels [27]. Dual wavelength technology has been adopted for optical flame detectors to minimize false alarms caused by other sources of IR radiation. The dual UV/IR flame detector employs UV with a high signal to noise ratio and a narrow band IR sensor.

Multi-Spectrum IR (MSIR)

Multi-Spectrum IR flame detectors use multiple infrared spectral regions to improve differentiation of flame sources from non-flame background radiation [24]. Additional IR channels (i.e. triple IR) makes the detector more immune to false alarms. This detector offers good speed with a range of about 60m, and can be used both indoors and outdoors. MSIR offers higher immunity from external IR radiation sources, such as arc welding, lightning, sunlight etc.

2.3.2 Heat detectors

Heat detectors are a type of fire detector that detects energy emission from a fire through heat. This means the detector is activated by currents of heated air, combustion products or by radiation. The two common types of detectors are “fixed temperature” and “rate of rise”. Fixed temperature detectors signal when a predetermined temperature point is reached. Rate of rise detectors signal when the temperature rises at a rate that exceeds the predetermined rate number. Heat detectors have a higher reliability factor than other fire detectors, which results in fewer false alarms. On the other hand, they are slower to activate and should only be considered for installation where activation speed is not considered critical [9].

2.3.3 Visual flame imaging detectors

Visual flame detectors employ standard Charged Couple Device (CCD) image sensors, commonly used in Closed Circuit Television Cameras (CCTV) and flame detection algorithms to establish the presence of fires [24]. Visual flame imaging does not depend on emissions of products of combustion. Rather, the method processes the live image from the CCD array, analyzing the shape and progression of fires to differentiate between flame and non-flame sources. As a result, they are commonly found in areas where it is required to differentiate between process fires and accidental release of combustible materials. Visual imaging flame detectors can not detect flames that are invisible to the naked eye, i.e. hydrogen flames, while also being feeble towards heavy smoke and other visual impairments.

2.4 Design and operational requirements

Concerning fire and gas detection systems, the PSA facilities regulations §32 states that for design of the system, the standards NS-EN ISO 13702 with Appendix B.6 and NORSOK S-001 Chapters 13 and 14 should be used [28]. The fire and gas detection system is independent from other safety systems and systems for management and control, but may have an interface with other systems as long as it is not negatively affected by a system failure or incidents in these systems.

Further, the paragraph states that facilities that are not permanently manned, also should have a dedicated gas detection function for the area around and on the helicopter deck. Detection of gas should be shown by means of a light signal that is visible at a safe distance from the facility. Other PSA paragraphs relevant for F&G systems are management regulations §5 Barriers, facilities regulations §8 Safety functions, and activities regulations §45 Maintenance & §47 Maintenance programme.

All activities that affect the safety life cycle of the SIS shall be managed and performed by personnel who are competent to do so in accordance with the relevant requirements in IEC 61508 and IEC 61511. The interaction between requirements and regulations used in this thesis are depicted in figure 2.8.

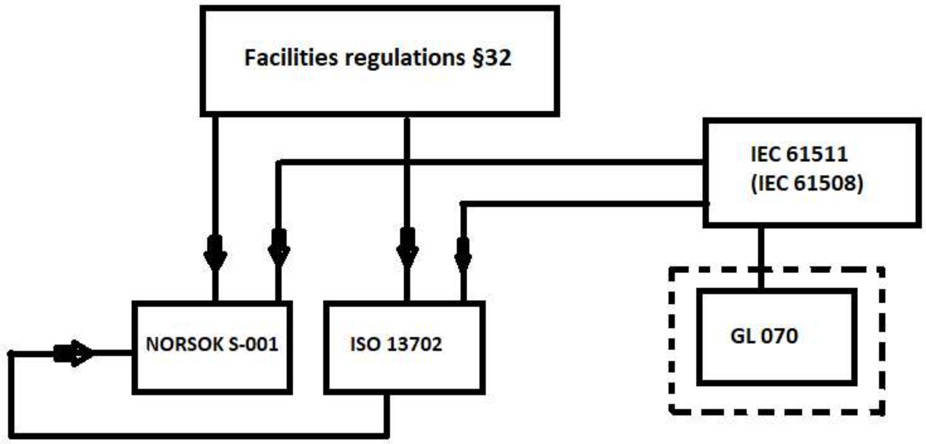


Figure 2.8: A graphic representation of interaction between standards.

2.4.1 NORSOK S-001

NORSOK S-001 is the standard for technical safety valid on the NCS. This includes the principles and requirements for the development of physical safety design of offshore installations producing oil and gas. Chapters 13 and 14 are used to present relevant information [29].

Gas detection

The standard states that the gas detection system shall monitor continuously for the presence of flammable or toxic gases, to alert personnel and allow control actions to be initiated manually or automatically to minimize the probability of personnel exposure, explosion and fire. The system is contingent on Uninterruptible Power Supply (UPS) to maintain gas detection if the main power supply fails.

Design principles

Design principles for gas detection are established based on gas characteristics. This includes light/heavy gas, flammability and toxicity. For best possible coverage, detectors should be installed according to results of a study of gas leakage scenarios within each areas. The study must consider leakage source and rate, dispersion, ventilation, placement of equipment and the probability of detection of small leakages.

The standard supplies a list of application principles for determination of detector locations:

- Natural flow corridors shall be covered.
- Detectors shall be placed in different heights in areas with different natural flow paths.
- Gases that are lighter and heavier than air, including temperature effects from release, shall be taken into account.
- Necessary protection from environmental impacts such as snow, sun, rain, wind and fog is important.
- Equipment enclosures shall be especially considered.

Regarding type of gas detector, a combination of open path/line detectors and point detectors should be used to optimize the coverage and detection probability. Detectors with arrangement for self-diagnostics and suited for relevant gas, should be used, these are preferably IR detectors. Catalytic detectors should only be used if proper detection performance by other types is not achieved.

Primarily, line detectors should be used, supported by point detectors where adequate coverage is not achieved. Conversion between line and point detectors is done applying the formula:

$$N_p = \frac{L_S * C_{LEL}}{LEL_m * 100} \tag{2.1}$$

Where N_p is the number of point detectors.
L_s is the length of line of sight.

C_{LEL} is the low alarm limit point detectors (%LEL)

LEL_m is the low alarm limit open path/line detectors.

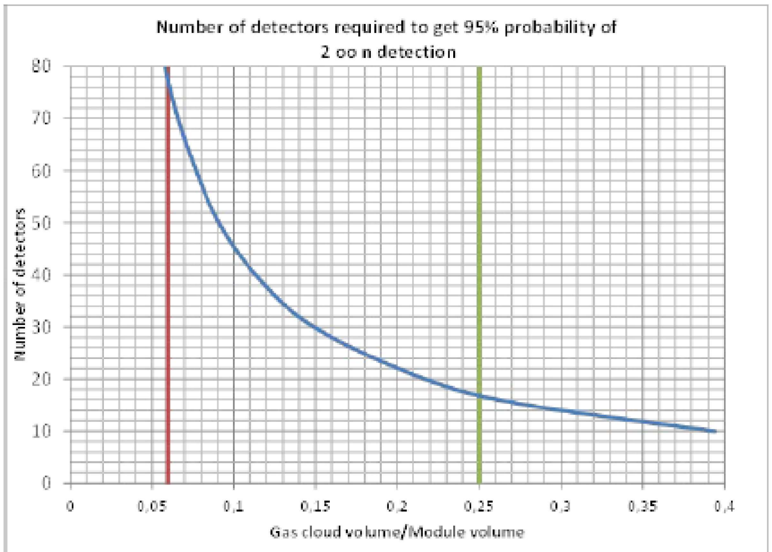


Figure 2.9: Number of point gas detectors as a function of gas cloud volume [29].

The target is that a gas cloud shall be detected with a 95% probability for confirmed detection on two detectors. Figure 2.9 shows number of point type detectors required to obtain 95% probability for confirmed detection on two detectors as a function of the detectable gas cloud volume relative to the volume of the module. The vertical lines at 0.06 and 0.25 represents typical upper and lower gas cloud sizes.

For confirmed detection of flammable gases in hazardous areas, using 20 % LEL level, a gas cloud of 10 meters in diameter should be detected anywhere in the area. As a practical approach for point detectors this can correspond to a distance of 7 meters between gas point detectors when voting is applied for confirmed detection.

Voting

Voting should include all detectors of any type within a detection area. With confirmed gas detection, a voting of 2ooN reaches specified alarm limit when $N \geq 3$. Confirmed gas detection on a single detector 1ooN and N>2 may be acceptable if the failure probability is documented as sufficiently low and yields manageable consequences. A faulty detector can either be treated as a gas alarm, or have an automatic reconfiguration from i.e. 2oo3 to 1oo2. A 1oo1 configuration should only be used for area monitoring and alarms.

Gas detection actions

The gas detection system shall initiate actions in accordance with the principles below and the safety strategy. Automatic initiation of action shall include

- Emergency shutdown (confirmed gas).
- Ignition source disconnection.
- HVAC shutdown (confirmed gas at air intake).
- Deluge activation in naturally ventilated areas to reduce explosion over-pressure/drag forces if specified in Safety Strategy (confirmed gas).
- EDP activation if specified in safety strategy (confirmed gas).
- Start of fire water pump when used for explosion mitigation (low gas detection).
- General alarm (confirmed gas detection).

Gas detection set points

The standard sets alarm limits for hydrocarbon detection:

- Low alarm for point detectors shall be maximum 20% LEL. For turbine enclosure 10% LEL.
- Low alarm for IR open path detectors shall be maximum 1 LEL_m
- High alarm for point detectors shall be maximum 30 % LEL. For turbine enclosure 15% LEL

- High alarm for IR open path detectors shall be maximum 2 LEL_m

If toxic gas detection is required, separate outputs for annunciation of toxic gas alarm should be provided.

F&G systems status shall be continuously available in Central Control Room (CCR), and the system shall raise alarm in CCR for operator awareness or action considering gas detection, failure to execute action upon demand or function defect or failure.

Response time

IR detector response time should be less than 5 seconds for general area applications, and less than 2 seconds if used in Heating Ventilation and Air Conditioning (HVAC) ducting. Acoustic detector response time including delays employed to improve false alarm immunity, should not exceed 30 seconds. The time from detector alarm limit until alarm is presented for operators should be less than 2 seconds. Adhering to these response time requirements ensures that the total reaction time for each safety function is within reasonable pace.

Fire detection

The standard presents that the role of the fire detection system is to monitor continuously for the presence of a fire to alert personnel and allow control actions to be initiated manually or automatically to minimize the likelihood of fire escalation and probability of personnel exposure.

Design principles

As a basis for layout of detectors, fire detection coverage in each area shall be based on flame size, smoke characteristics and temperature rise. The target for critical fire detection is that a flame size of 0,5 meter in diameter and length of 1 meter is to be detected by at least one detector. While a flame size of 1 meter in diameter and length of 3 meter is to be detected by at least two detectors (corresponding to an ignited gas leakage rate of 0,1 kg/s). Flame detectors shall be located such that the likelihood of false alarms being initiated is minimized. To fulfill this criteria, direct exposure to flame radiation from sources such as flares or reflections from shiny surfaces should be avoided.

Detector characteristics and calibration shall ensure detection of a fire condition at an early stage, and the detector shall be capable of operating under the conditions at the time that fire detection is needed. Fire detectors shall be self-monitoring and should include provisions of self-diagnostics to the extent available. Based on a typical flame detector characteristic, the distance between flame detectors and the monitored target should not exceed 26 meters. Heat detectors should be used in high-risk areas where other detection principles are not suitable. Maximum distance between sensors in normal ventilation should be 7 meters with a maximum wall distance of 4,5 meters. Maximum distance between sensors in a mechanically ventilated area is 9 meters with a maximum wall distance of 4,5 meters as well. When suitable according to area conditions and fire characteristics, flame detectors are preferred over heat sensors.

Fire detection actions and voting

According to the standard, a fire alarm should be raised upon activation of any fire detector, and confirmed fire should be based on voting between two or more fire detectors in alarm. Confirmed fire detection and applied voting principle for automatic actions shall be defined in the safety strategy.

Upon fire detection, recommended actions are:

- ESD2 (confirmed fire in hazardous area)
- Emergency depressurisation (confirmed gas)
- HVAC and fire damper shutdown except for areas subject to smoke control (confirmed fire)

- Activation of firefighting equipment (confirmed fire)
- General alarm (confirmed fire detection)
- Start fire water pump

The system should raise alarms in CCR to make the operator aware of detection of fire, failure to execute action upon demand or function defect or failure.

Voting should include all fire detectors within a detection area exposed to the same fire scenario. The standard delivers voting guidelines for smoke, flame and heat detectors:

- Smoke

  2ooN detectors to reach specified alarm limit when N $\geq$ 3

- Flame

  2ooN detectors to reach specified alarm limit when N $\geq$ 3

- Heat

  1ooN detectors to reach specified alarm limit when N $\geq$ 2

The number of detectors that may simultaneously be inhibited or in fault, depends on detection coverage and area risk. A 1oo1 voting detection principle should only be used for area monitoring and alarms.

Response time

Response time of the fire detection function shall be considered and documented in the safety strategy. Standardized response times shall be defined for groups of similar F&G functions except when individual F&G functions require exceptional response time to meet intended functionality. There shall normally be no predefined delays of fire detection.

2.4.2 ISO 13702

ISO 13702 is an international standard that describes requirements and guidelines for control and mitigation of fires and explosions on offshore production installations in the petroleum and natural gas industries [14]. The objectives of this standard is to ensure the safety of personnel, protection to the environment and assets and minimization of financial and consequential losses from fires and explosions.

According to the standard, the objectives for a fire and gas detection system is to provide continuous monitoring functions and alert personnel of the presence of a fire or flammable gas. Further, it should allow control actions to be initiated to minimize escalation, manually or automatically. The appendix, section B6, of ISO 13702 presents the same design and location principles for fire and gas detection systems as NORSOK S-001. The fire and gas detection system shall be designed to detect hazardous accumulations of flammable gas, detect leaks and fires at an early stage.

A fire and explosion strategy gives the basis for determination of location, number and types of detectors. The strategy should be based on the identification and assessment of possible hazardous fire and gas events in each area. After identification, the requirements to reliably detect events is evaluated. Detectors are selected based on response characteristics and experienced conditions when detection is required. These detectors must be suitable for their location and approved by a recognized authority. The fire and gas detection system shall facilitate testing of detectors, internal functions and outputs.

Fire protection is divided in two parts in the standard - active and passive fire protection. Their objectives coincide on some areas, as they both are to limit escalation and allow emergency response. Active fire protection is tasked with controlling fires as well as attempting to extinguish and limit damage to structures and equipment. Passive fire protection is placed to maintain functionality of critical safety systems.

The standard also gives recommendations on inspection, testing and maintenance. Safety systems relevant to this standard shall facilitate a demonstration of total system functionality in a realistic environment. In order to provide effective procedures, systems shall be tested prior to first use, confirming that the functional requirements are met. A detailed written maintenance scheme containing inspection and testing routines and frequencies, should be followed closely.

All systems need to be thoroughly tested and inspected according to an established maintenance procedure. The maintenance procedure should include regular visual inspections, as well as regular appropriate operational testing. The latest inspection report should be available on the installation. Use, impairment, failures and restoration of equipment relevant to the system must be reported, and corrected if possible. If the system can not be corrected swiftly, a contingency plan must be implemented. The reports from inspections, maintenance and testing shall be periodically reviewed to confirm that the maintenance scheme is adequately implemented.

Figure 2.10 presents typical application of F&G detectors according to the appendix of ISO 13702.

Fire and gas system				
Hazard	**Type of detector**		**Typical application**	**Typical actions**
Fire	Heat	pneumatic	Process, wellhead, utilities	Alarm, ESD, EDP, closure of the SSSV, active fire protection
		electric	Turbine hoods, workshops, stores, engine rooms, process, wellhead, utilities	Alarm, ESD, EDP, active fire protection
	Flame		Process, wellhead utilities, generators, turbine hoods	Alarm, ESD, EDP, active fire protection
	Smoke		Control rooms, electrical rooms, computer rooms, accommodation	Alarm, isolate power, active fire protection (if present)
			Air intakes to TR and control stations	Alarm, isolate ventilation
Flammable gas			Process, wellhead, utilities areas[a] engine rooms[a]	Alarm, ESD, EDP, isolate power
			Air intakes	Alarm, ESD, EDP, isolate power, ESD ventilation system
Oil mist			Enclosed areas handling low GOR liquid hydrocarbons	Alarm, ESD, EDP, isolate power
	Manual call point		All areas, escape routes, muster points, TRs	Alarm, start of fire pumps
NOTE Process areas include drilling areas.				
[a] For rooms containing safety systems which might be operating during the emergency.				

Figure 2.10: Typical applications of fire/gas detectors according to ISO 13702 [14].

2.4.3 GL 070

GL 070 is the standard for application of IEC 61508 and IEC 61511 for the Norwegian petroleum industry. ISO 13702 states that methods for determining requirements for electrical, electronic and programmable electronic systems and guidance on how these requirements can be achieved are given in IEC 61511-1. This guideline differs from the other two presented in this thesis, as it focuses on SIL requirements, safety functions and PFD calculations. The guideline approaches fire and gas detecting by focusing on detection with one detector, a 1oo1 voting strategy.

Gas detection

As the aforementioned standards, GL 070 also states that gas detection is generally based on either point detection and line detection. This guideline treats the detection system as a function and asserts that for point detectors the function starts when the detector is exposed to gas, and ends with the signal given from the F&G system. For line detectors the function starts when the detector beam is exposed to gas, and ends with the signal given from the F&G system.

The F&G detection system will have different actions based on configuration of the logic. There are different actions depending on where the gas is detected, i.e. (signal is given at 20 % of LEL) and the implemented voting, in this case also 1oo1.

Component	**Voting**	**PFD**			
		Catalytic	**IR point**	**IR line**	**H_2S**
Detector	1oo1	$7.9 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$
F&G logic (single I/O and redundant CPU)	1oo1	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
Total for function		$\mathbf{9.4 \cdot 10^{-3}}$	$\mathbf{4.1 \cdot 10^{-3}}$	$\mathbf{4.1 \cdot 10^{-3}}$	$\mathbf{3.7 \cdot 10^{-3}}$

Figure 2.11: PFD results for gas detection with one detector [30].

The results indicate that each of these functions fulfils a quantitative SIL 2 requirement. However, the catalytic gas detection is just within the SIL 2 requirement. To improve the PFD, more frequent proof testing or use of detectors with verified higher reliability should be considered (i.e. IR detectors).

Flame detection

The guideline states that the F&G detection system consists mainly of detectors and F&G logic solvers. Fire detection is generally based on three principles; smoke detection, heat detection and flame detection.

If a fire central or some other equipment is used to interface between the detector and the F&G system, this has to be included in the calculations. This has not been done in the example calculations in figure 2.12. Considerations related to the number and layout of detectors, should be covered by separate studies (i.e. simulation studies).

(a)

Component	**Voting**	**PFD**		
		Smoke	**Heat**	**Flame**
Detector	1oo1	$2.2 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$
F&G logic (single I/O and redundant CPU)	1oo1	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
Total for function		$\mathbf{3.7 \cdot 10^{-3}}$	$\mathbf{3.7 \cdot 10^{-3}}$	$\mathbf{3.7 \cdot 10^{-3}}$

(b)

Figure 2.12: (a) A block diagram of the fire detection sub-function according to GL 070. [30]
(b) PFD results for the fire detection sub-function with one detector. [30]

The results from figure 2.12 indicate that each of these F&G functions fulfils a quantitative SIL 2 requirement. Analyses should be conducted to verify that the minimum SIL-requirement gives an overall acceptable risk when all fire detectors are taken into consideration. Number of detectors that should function in a fire scenario, placement, scenarios where the system is demanded, and common cause failures should be considered.

2.5 Investigated operational incidents

The safety of personnel and preservation of the environment are paramount in such a dangerous industry as the O&G sector. F&G proposes a great risk if undetected or on facilities with poor barrier management. The general trend is that the financial impact for major incidents is continuously increasing as well. Nolan [9] states that there is a great benefit from reviewing incident data to learn from past mistakes and construct design improvements to remove undesirable operating procedures. This relates to to the safety of personnel and environment as well. According to the study most incidents occur during periods of maintenance activities, start-up or shut-down. Figure 2.13 shows how cost of failures have increased the past decades.

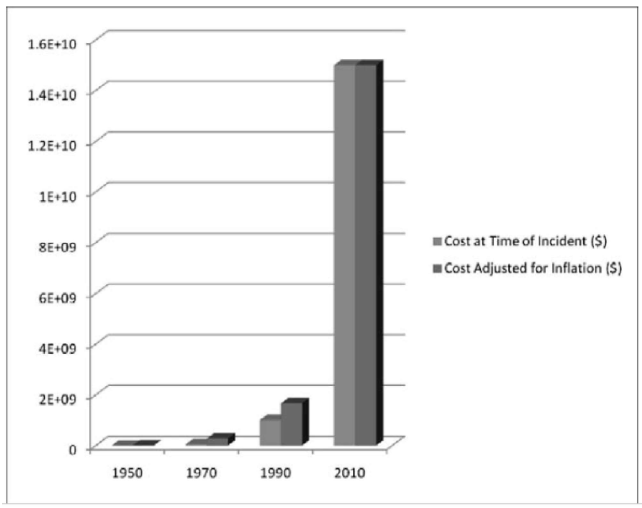


Figure 2.13: Historical financial loss due to major incidents [9].

Below are selected incidents or system conditions audited by PSA Norway either because of insufficient F&G detection or poor barrier management. These are cases where PSA Norway have deduced as not in accordance with relevant standards. This thesis focuses mainly on anomalies opposing with PSA's facilities regulations §§29-40 Physical barriers. All reports are publicly available through PSA's website.

2.5.1 Equinor - Åsgard A - Barriers

The goal of this PSA audit was to verify that Equinor's management and follow-up of barriers was in accordance with governmental regulations, as well as to verify safety readiness. This includes processes that secures the safeguarding of assumptions, prerequisites,

Figure 2.14: The production ship by Åsgard. Photo: Øyvind Hagen, Equinor

limitations and recommendations in the risk analysis for Åsgard A, and that these are communicated throughout the organization. Anomalies detected during audit included fixed fire-fighting system and gas detection.

Fixed fire-fighting systems

The fixed fire-fighting system did not yield adequate firewater coverage in explosion zones or zones with great fire risks on the tank deck on Åsgard A. A function test on a fire monitor on the tank deck showed a limited coverage around the monitor itself. Hydrocarbon pipes, flanges on oil pumps and cable gates were not fire protected by the monitoring system on the tank deck. Performance requirements were not described to personnel performing the monitor testing, and it was not decided how the requirements were to be made visible in the future maintenance scheme for Åsgard A.

Gas detection

There was a lack of gas detection during certain weather conditions. The regulations states that appliances should have a gas detection system that secures rapid and reliable detection. There were especially issues surrounding snow, but also rain could diminish detection, which could occur 2-3 times in a 14 day period. It was clarified that it was not procedure to shut down production and depressurize during these events. The PSA stated that the gas release system might have had shortcomings as there were no test results from depressurizing during normal operations. The full audit is available at PSA's website [31].

2.5.2 Aker BP - Ula - Risk management

Figure 2.15: The three platforms on the Ula field, from Aker BP's website [32].

PSA states in this report that there was a need to give more attention to the coherence between risk-, barrier-, and maintenance management. The goal of the audit was to assess how the operator secures compliance to governmental regulations and company requirements for management of major accident risk, barriers and management on Ula.

To compensate for lacking and inadequate passive fire protection, there is a requirement for evacuation within five minutes. The operator was unable to document the consequences of liquid fire after five minutes, leading to the conclusion that evacuation within five minutes is a weak measure, especially considering the insecurity regarding consequences of fires. Anomalies detected during audit included faults in barrier management, passive fire protection and the gas detection system.

Gas detection system

There was an inadequate ability to reliably detect gas rapidly. PSA was informed of frequent events with fault detection resulting in fault alarms from line gas detectors. The fault alarm gives an alarm centrally and leads to an operator having to go out in the field to check for alarm causes. The detector automatically went into a failure mode called "beam blocked" leading to a weakened ability to detect gas by the detector. This crippled the safety function and the opportunity for reliable gas detection. Systematic technical measures to improve the situation had not been implemented. The full audit is available at PSA's website [33].

2.5.3 Aker BP - Ivar Aasen - Barrier management

Figure 2.16: The Ivar Aasen platform, operated by AKER BP [34].

PSA controlled Aker BPs work in implementing barrier management in accordance with regulations and requirements on Ivar Aasen in September 2014. The goal was to supervise Aker BPs establishment and implementation of control systems securing compliance of demands in a life cycle perspective.

One deviance and five points for improvement were identified during the audit. The deviance is related to the choice of common network solutions for control and safety systems: The fire and gas detection system could not perform intended functions independent of other systems. Detection of fire and gas involves actions preformed by the emergency shut down system. These signals were planned to be sent over a joint network for control and safety systems. Even though this network has high integrity, the safety functions may be influenced negatively as a result of the pairing.

A system for barrier management, fire water supply, ignitions source control and fire and gas detection were points for improvement according to the audit.

Facilities should have a fire and gas detection system securing rapid and reliable detection of starting fires and gas leakages. When detected, automatically controlled actions should limit consequences. PSA stated that there were "insecurities surrounding chosen solutions for fire and gas detection meet these regulatory requirements".

Based on the safety strategy for the Ivar Aasen platform, PSA identified some conditions in conflict with NORSOK S-001 guidelines.

- The company safety strategy states that ≪Heat detectors shall be installed in the transformer area where transformer-oil fires may arise, confirmed detection will give alarm for manual intervention≫. Referring to table 3 in NORSOK S-001 14.4.5. [29] heat detectors are deemed unsuitable for this practice due to low reliability, slow response time and time consuming functional testing compared to other types of detectors.
- The safety strategy describes principles for voting of gas detectors where a 2oo2 voting is prominent, i.e. machine rooms with fire water pumps and emergency generator. This is solutuions where stand alone failures may lead to safety functions not working properly. The investigating team refers to NORSOK S-001 13.4.3 for gas detection actions and voting.
- "Confirmed gas detection at combustion air intake shall not shutdown the Firewater pump generators and emergency generator". Referring to NORSOK S-001 19.4.2 UPS, the action of not shutting down the emergency generator when there is confirmed gas in the combustion air intake, was questioned.

The full audit is available at PSA's website [35].

2.5.4 Equinor - Mongstad - Investigation of gas leakage

Figure 2.17: A landscape shot of Mongstad Refinery from Equinors web page [36].

The gas leak at Mongstad in October 2016 occurred when an operator tried to operate a valve, after detection of gas in the area. Corrosion under insulation had lead to the valve socket being completely rusted, culminating with the valve breaking giving the gas free expiration. ESD and manual depressurization were immediately initiated, while alarm activation made personnel evacuate the facility.

The investigation revealed some deviations. The facility had not been properly maintained, there was a lack of risk assessment, and poor personnel control during evacuation. There was also inadequate gas detection, a lacking system for EDP, and an ineffective alarm system.

Inadequate gas detection

From the company's technical integrity management program it became clear that some parts of the facility lacked gas detection completely, while in other areas possible detection was sub-optimal.

The full audit is available at PSA website [37].

2.6 Moving forward

This chapter has given an overview of F&G detection techniques that will be used further in the thesis. Some of the F&G detection equipment seems more relevant than others to ensure high reliability and robustness. Some of these can be put on a mobile inspection robot and will be discussed in chapter 4 & 5. Not all facility incidents presented in the last section are directly relevant for an unmanned facility. However, the most important experiences concerning problems with F&G systems seems benefiting to bear in mind further along the thesis, especially for analysis of design.

Finding the correlation between regulations and requirements and practical use, combined with the knowledge from reviewed incidents, seems important to avoid design and operational problems as much as possible when moving into more uncharted territories concerning F&G detection on an unmanned platform. To use this gathered information, it is needed to review robotic solutions that are compatible with inspection, testing and maintenance tasks. This is done in the next chapter.

Chapter 3

Robotics for unmanned facility inspection and maintenance

A literature study was conducted to investigate historic and current development in the use of autonomous mobile robotics for inspection and maintenance purposes. Both the oil and gas industry and other relevant industries were targeted in the search. To get a clearer view of the possible working environment for a robot, the design of unmanned facilities were investigated. This includes access methods and inspection and maintenance philosophy for unmanned facilities.

3.1 Industrial use of mobile robotics

The use of ROVs for inspection on subsea fields are widespread in the industry. Further, autonomous underwater vehicles (AUVs) are now increasingly being used. These are robots that can perform pre-programmed tasks without needing human input during the operation. As the idea of unmanned platforms are becoming more realizable, the need for robotics that can be either remotely controlled or run autonomously is apparent.

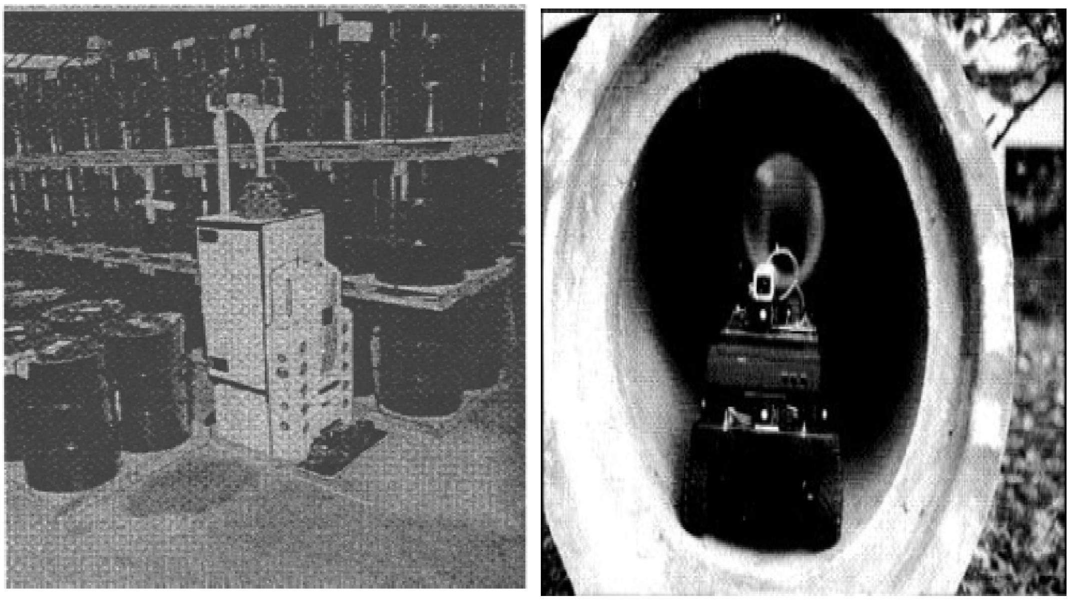
In the pre-study for this master thesis, a series of interviews with industry partners were conducted. When asked about the current situation for robotic solutions, one subject said that crawlers for online tank floor inspection are currently available. Inspection methods that are implemented includes visual inspection and ultrasonic testing for measuring remaining wall thickness. Some crawlers are able to cope with limited deposit. Some robots are capable of performing a scan autonomously [1].

The first crawlers capable of navigating a processing plant have been introduced, these are capable of taking samples, video recordings and performing simple actions. Further plans for developing a scaled-down version that can be smaller and cheaper are in a final decision stage [38]. Arm and snake robots have successfully been used for certain industrial inspections and service tasks recently. Especially subsea, where i.e. the Eelume concept have showed promise, being piloted at the Aasgard field [39].

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

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

Interest in the use of mobile robotics for inspection and maintenance services has been around for many decades. Already in 1995, The Stored Waste Autonomous Mobile Inspector (SWAMI), portrayed in figure 3.1a, a prototype mobile robot designed to perform autonomous inspection of nuclear and hazardous waste storage facilities, was tested [40]. In 1997, a German prototype study was published that describes KURT, an autonomous robot platform prototype that is able to navigate through a network of sewage pipes in Emscher [41]. KURT was a six-wheeled vehicle with modular, showed in figure 3.1b, layered hardware and control architectures. The robot included mostly stationary sensors and one flexible ultrasound transducer and two inclinometers.



(a) SWAMI [40]. **(b)** KURT exiting a sewage pipe [41].

Figure 3.1: 90's robotic solutions

Figure 3.2: A standard crawler for sewage inspection according to [42].

In 2012, the same company released another paper revolving use of crawler robots in the Emscher sewers, showcasing the vibrant development of technology since the 90's [42]. Figure 3.2 shows an example of a standard motorized crawler with a video camera, extended to its full height at 1 meter. While inspecting and detecting the condition of the Emscher sewer system, corrosion, mechanical wear, inhibition of flow, cracks and leaks are reliably detectable.

The MAINBOT project started in 2013 developing service robots applications to autonomously execute inspection tasks in extensive industrial plants on equipment that is arranged horizontally using ground robots, or vertically using climbing robots [43]. MAINBOT proposes using service robots to autonomously execute inspection tasks. A ground robot with a mobile manipulator composed of a mobile base and a 6 Degrees of Freedom (DOF) manipulator, and a vertical robot consisting of a mobile base and an internal arm for inspection system positioning, was developed. The ground robot experiment consisted of moving in a solar field, reaching different inspection areas in the plant and stopping at pre-established points. The climbing experiment revolved moving in a vertical structure, a tower. Eddy current and thermography based algorithms was developed and integrated in the robotic platforms.

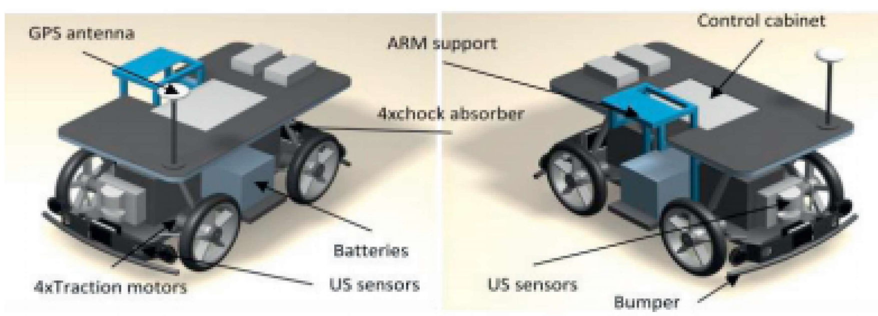


Figure 3.3: The ground robot proposal [43]

In the wind industry, Sandia National Labs has developed a robotic blade inspection system [44]. The robot uses vacuum technology for adhesion and can move up and down and from side to side on the surface of a blade and gather high resolution images to detect surface damage and also detect internal defects through the use of phased array ultrasonic imaging technology. The robot is depicted in figure 3.4. Bogue [45] presents recent research on this and other uses for climbing robots.

Figure 3.4: Sandia's crawling robot with infrared cameras to look for hidden wind blade damage [44].

In 2011, MIMROex became the first proof of concept of a mobile autonomous robot performing inspection tasks on a shallow water offshore gas platform [46]. The robot was equipped with a 6-axis robotic arm carrying a camera for visual inspection, while stereo microphones and a gas and fire sensor were attached at the robot base. The robot autonomously recorded sensor data and performed continuous sensor recording along a predefined path. All inspection task results were saved to a database for review. The system was designed to operate in explosion zones and certifiable according to IEC 60079, the standard for explosion protection.

A year later, the Sensabot robot, a ROV designed to work in flammable and explosive environments, was shown to be able to perform remote controlled inspection task on an onshore oil and gas facility [47]. The robot was equipped with an extendable arm to perform sensor measurements at different heights and angles. The robot provided a forward-looking laser and a 360° view from six cameras, one of which a powerful zoom camera allowing the operator to obtain magnified views of small or distant objects. The prototype for this robot is shown in figure 3.5.

Figure 3.5: The Sensabot prototype [47].

DORIS [48], shown in figure 3.6, is an autonomous rail-guided robot designed for inspection and monitoring of topside (O&G) facilities. A real-world demonstration showed that DORIS was able to fully navigate on the 130m 3D rail path by teleoperation via Wi-Fi. The system was able to autonomously identify operational anomalies and send alarms to remote operators. The operators were able to access the embedded sensors for real time information of the monitored environment and the robot conditions. DORIS attributes a laser scanner, HD camera, stereo camera, infrared camera, microphone, gas sensor and a manipulator.

Figure 3.6: The first prototype of DORIS [48].

In 2019, a project regarding offshore High Voltage Direct Current (HVDC) converter stations for transportation of offshore wind energy was implemented. The paper presents field testing of an autonomous mobile robot for inspection and surveillance on an offshore platform in the North Sea [49].

The tests were performed with ANYbotics' quadrupedal robot ANYmal, which is designed to navigate through difficult environments with its legged locomotion, in comparison to wheeled or tracked actuation. Figure 3.7 shows the deployment of ANYmal on one of TenneT's offshore HVDC platforms.

Figure 3.7: ANYmal deployed for autonomous inspection and surveillance on a wind energy HVDC converter platform in the North Sea [49].

Mounted on the robot is an actuated gimbal with a visual and thermal camera and a flashlight. Other features are microphones for audible and ultrasonic sound recordings. The report shares images of how the robot handles basic hinders on a platform such as stairs, door stills and pipes, as well as cable protection and leakage protection. The robots mission was to perform daily inspection tours, including reading instruments, assessing equipment health and detecting anomalies.

The robot was tested on site for two weeks, executing over 30 autonomous missions, containing 19 check points each mission, with 25 minutes used for each round. The researchers stated that the robot successfully tested visual, acoustic and thermal inspections and identified an emergency alarm with its microphone. In conclusion, the robot was found well suited for autonomous inspection, making a case for use of legged robotics. For further work it was recommended integrating the inspection sensors in a robotic arm to increase the coverage of points of interest for inspection.

Different from the other robots, the Taurob Tracker uses belts as a means of progress. The Taurob Tracker system is a reconnaissance robot for emergency personnel. By means of remote control, this robot is able to penetrate areas that are contaminated by harmful substances (gases, radiation, liquids) and is therefore inaccessible to personnel or dangerous and can therefore only be accessed with considerable risk and effort.

The system is equipped with multiple cameras, in order to transfer live images: One camera at the front and rear in the housing respectively, as well as various optional cameras on the arm. LED headlamps are also located in the vicinity of each of the cameras, ensuring good illumination in darkness. At the end of the arm is an optional gripper or a retainer for measuring devices. An infra-red camera is optionally integrated in or on the last element of the arm. The Taurob Tracker is thoroughly presented in the pre-study [1].

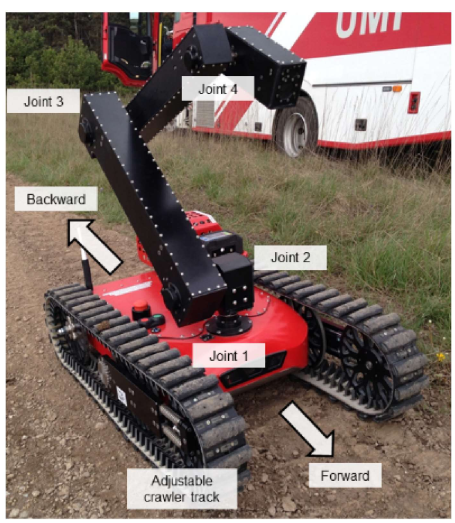


Figure 3.8: The Taurob Tracker.

3.2 Unmanned facility design

This thesis does not only focus on robotics and F&G detection, it is also important to establish where it is useful to employ robotics for these tasks. One interview subject in the pre-study said the industry will need to think in new directions when implementing robotics, not just let robots take over human tasks, as they might be too complex and too many. Everything needs to be done in design first, and then what is left is for the robots is, i.e. small interventions, turning valves and visual inspections. Therefore, how to design platforms readily built for unmanned activities, is a crucial point for success.

3.2.1 Industry Development

With the current low oil prices, the industry has to consider cost-effective solutions to explore natural resources on the NCS. The concept's benefits include lower CAPEX and OPEX, as well as reduced safety risks as no personnel have to stay on the platform. As companies move oil platforms farther offshore and into other remote, challenging locations to find oil and gas, managing those operations efficiently while reducing risk to workers will become increasingly important.

One of the pioneers within unmanned platforms is Equinors Oseberg H, situated at Oseberg Vestflanken 2, a project which aims to extend the life of the Oseberg field to 2040, paving the way for unmanned platform projects in the region. It is the first fully automated oil and gas platform, entirely unmanned and requiring only one or two maintenance visits a year.

The platform started production in October 2018, and is remotely controlled from the control room on the Oseberg field centre 8km away from Oseberg Vestflanken. In case of incidents the control room will take necessary actions to ensure safety on the platform. This process is very similar to the operating of remotely operated subsea wells and installations done within the industry for decades [50]. Oseberg H is the first platform of its kind on the NCS, having no personnel facilities on board. While performing inspection or maintenance, personnel will live on connecting to the platform with a Walk-to-Work bridge.

Figure 3.9: The unmanned Oseberg H Vestflanken 2 wellhead platform and the Askepott drilling rig [51].

3.2.2 Access methods

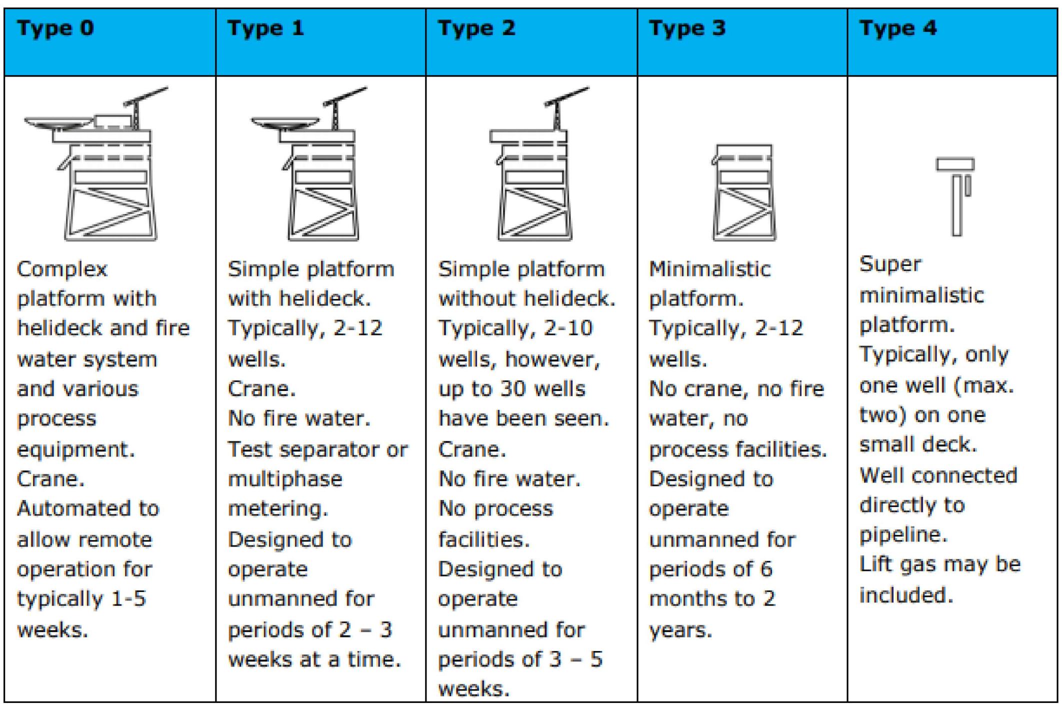
There are several potential access methods to an unmanned platform. One possibility is by helicopter. Challenging this approach is access by either a Fast Rescue Boat (FRB) or a Walk-to-Work (W2W) bridge on a support vessel. Alternatively, access from Offshore Service Rig (OSR), a jack-up service rig, is possible.

DNV GL has initiated a joint industry project to prepare a guidance for use of a W2W [52]. They describe it as a mode of facility manning "*to assist offshore facility operators in achieving safe and efficient personnel transfers to/from their facilities via a gangway system on a workboat, ship or semi-submersible unit*". As a result, the company has made a standard for classification of offshore gangways called: **DNVGL-ST-0358 Certification of offshore gangways for personnel transfer** [53]. In example, Kongsberg Maritime has taken this one step further, making a fully automatic integrated gangway designed to this standard [54].

Holt et al. [55] concluded that W2W manning solutions can increase workforce flexibility and utilisation, improve safety and reducing risk associated with offshore industry, as well as reducing costs. A suggestion promoted was that if the support vessel could i.e. provide W2W, hotel, helipad and ROV inspection, the benefits can be significant, making offshore facilities smaller, simpler and cheaper to operate.

3.2.3 Platform types

Rambøll categorizes unmanned wellhead platform concepts into five categories, ranging from type 0 to type 4 [56].



Type 0	Type 1	Type 2	Type 3	Type 4
Complex platform with helideck and fire water system and various process equipment. Crane. Automated to allow remote operation for typically 1-5 weeks.	Simple platform with helideck. Typically, 2-12 wells. Crane. No fire water. Test separator or multiphase metering. Designed to operate unmanned for periods of 2 – 3 weeks at a time.	Simple platform without helideck. Typically, 2-10 wells, however, up to 30 wells have been seen. Crane. No fire water. No process facilities. Designed to operate unmanned for periods of 3 – 5 weeks.	Minimalistic platform. Typically, 2-12 wells. No crane, no fire water, no process facilities. Designed to operate unmanned for periods of 6 months to 2 years.	Super minimalistic platform. Typically, only one well (max. two) on one small deck. Well connected directly to pipeline. Lift gas may be included.

Figure 3.10: Overview of the types of unmanned platforms according to a report by Rambøll [56].

Type 0

The type 0 platform concept is almost identical to a manned platform, but on a smaller scale. The platform is designed for frequent manning and can facilitate overnight stays for personnel. Typical manning frequency is ranging from once a week to daily visits. Supervisory Control And Data Acquisition (SCADA), ESD systems and F&G systems are separate. The F&G systems are both fixed.

Type 1

A type 1 platform is designed for manning by helicopter during daytime and an emergency shelter in case of poor weather conditions, making a return impossible. The ESD systems, F&G systems and SCADA systems are integrated into one common logic solver or computer. The F&G systems are both fixed.

Type 2

A type 2 platform has no overnight facilities available and is designed for manning by a Fast Rescue Boat (FRB). The FRB is launched from a standby vessel nearby given daytime and calm weather conditions. The FRB acts as the crew facility and stays by the platform when it is manned. Wellhead control, ESD systems, F&G systems and SCADA systems are integrated into one common logic solver or computer. Fire detection is fixed based on fusible plug loops and hand-held gas detectors, small fires are fought with hand-held extinguishers when the facility is manned. If the fire is major, the focus is on fast and efficient evacuation.

Type 3

A type 3 platform concept rely on noble materials, equipment with high documented reliability and usage of inherent safety principles. The primary method of access is by walk to work bridges from a standby vessel, with the use FRB permitted only on specific occasions. This vessel will be connected to the facility during operation and maintenance and act as crew hospitality, as there is no shelter on the platform. The platform is typically monitored by Closed Circuit TV (CCTV) and controlled remotely. ESD systems, F&G

systems and SCADA systems are integrated into one common logic solver or computer. The fire detection is fixed, based on fusible plug loops and hand-held gas detectors, for situations where the facility is manned.

Type 4

The type 4 platform concept is super-minimalistic and the facility is small with 1 or 2 wells. This type is not currently found on the Norwegian Continental Shelf (NCS), but mainly in the Gulf of Mexico and the Dutch sector of the North Sea. Evacuation from the platform is pointed directly back to the FRB bringing personnel on board the platform. The platform is equipped with a fusible plug loop as the only means of fire detection. The focus in case of fire is fast evacuation, as there are no other lifesaving appliances on site.

3.2.4 Maintenance and operations

Information gathered from interviews in the pre-study [1], and the unmanned facility report from Rambøll coincides well. When addressing unmanned facilities, the main issue with maintenance philosophy is that O&M activities should be designed out of the equation wherever possible. This is to minimize manning hours and frequency. There should be as little equipment and systems as possible on board, and equipment requiring periodic inspection for re-certification should be avoided.

Robust materials should be selected to reduce the need for RBI considerably. Focus should be on the specification and procurement of equipment with high reliability, high MTBF and short MTTR. Further, equipment should have a modular design where possible, and at least where it is designed for rare visits and short maintenance campaigns. This makes it possible to replace complete modules quickly, removing the process of repairs on facilities. Equipment in need of periodic inspections as i.e. fire extinguishers and inflatable life rafts can be brought to the installation.

The operations and maintenance philosophy should define how the platform is operated and the lifetime of the platform. Important points to consider are how often the facility should be visited, whether the facility should be in operation or not during visits, and in which matter the facility should be manned (helicopter, FRB, W2W bridge or other). Distinguishing which type of personnel are boarding the facility is also an important aspect; Should it be crew for a host or a specialist team from shore. Other attributes are i.e. logistics for consumables as chemicals, power and hydraulics, goals for production, regularity and uptime.

A O&M strategy for unmanned facilities should address the level of automation including needs for condition monitoring and preventive maintenance. It should also define which operations that can be performed remotely and which would require manning. The O&M strategy will depend on the mechanical handling strategy being developed for the platform.

Rambøll [56] presents inspection and maintenance philosophies for each type of unmanned platform:

Type 0

The operation and maintenance philosophy for the type 0 platform is similar to a philosophy for manned installations. Typically, a 40% to 60% distribution between scheduled and unscheduled maintenance is accepted. The platform type is equipped with a helideck, meaning maintenance activities can be based on the undemanding availability of helicopters.

Type 1

The philosophy surrounding this type of platform is to reduce operation and maintenance activities by avoiding equipment in need of periodic inspection or re-certifications as much as possible, and selecting equipment with a proven record with high reliability. Reliability Centered Maintenance (RCM) and Risk-Based Inspection are introduced for this type of facility, as well as some elements of preventive maintenance and condition monitoring. Typically, there are between 5000 and 6000 manned hours on the platform each year, with a manning frequency of once every 2-4 weeks.

Type 2

As with type 1, operation and maintenance activities are reduced as much as possible by selecting reliable equipment while avoiding equipment in need of periodic inspection or re-certification. Major maintenance is planned and scheduled during the summer months using an FRB. The typical manning frequency is once every 3-5 weeks, with a total number of man-hours in the range of 1.500-3000 hours per year. Elements of RCM, RBI, predictive maintenance and condition monitoring are part of the strategy.

Type 3

Operation and maintenance activities are reduced to a minimum. System and equipment are selected prolong maintenance intervals and optimize production uptime. Visiting frequency is very low; in the range of once every 6-24 months, depending on operator philosophy, as well as keeping the number of man-hours on the facility below 500 hours per year. Typically, maintenance work is planned to be performed during the summer months when the platform are on a planned shut down. RCM, condition monitoring and preventive maintenance are the prevailing part of the strategy, as the use of robust materials minimizes RBI requirements.

Type 4

Operation and maintenance activities for type 4 platforms are reduced to an absolute minimum, so is also the systems and equipment, often referring to American Petroleum Institute (API) recommendation for inspection and testing. Some failures are expected and handled on planned visits. The manning frequency is relatively high, around once a week, this is made possible due to a typical location in shallow waters close to shore. Therefore, the design is not necessarily optimized to reduce manning hours or frequency.

3.3 Moving forward

The current design and technologies used on robotics across several innovative industries provides the basis for discussion on design implications for robotics on unmanned facilities. One of the thesis goals will be to create a suitable combination of inspection equipment mounted on a robot inspired by presented solutions. Based on literature reviewed in this chapter, choosing type of platform to combine with autonomous robotics should be possible. Which implications the type of platform choice has, will be discussed in chapter five.

In the next chapter, criteria necessary to implement robots for inspection tasks will be discussed, using gained knowledge from thesis chapter two and three, as well as information from the pre-study.

Chapter 4

Implementation of inspection procedures for mobile robotics

Employing an autonomous robot on an unmanned platform raises some challenges. One important challenge is to change an inspection procedure from human to robotic intervention, a scenario most relevant on an unmanned platform. Preferably, this should be performed autonomously by the mobile robot. There are some possible scenarios where the robot might have to respond regarding F&G detection. How the robot should respond to low alarm, high alarm and detected gas are important factors to consider. Additionally, if there are fixed sensors available, a big part of the robotic tasks will be to perform functional testing of gas sensors as well as monitor and reading instruments. In this case, testing of gas detectors will be the main focus, although robotics might be utilized for a numerous of other inspection and maintenance aspects.

It was granted access to a test procedure concerning F&G detection from one of SUBPRO's collaborators, henceforth portrayed as "the company". A summary of the concept and task procedures are given in the appendix. The company plans and procedures, along with regulations and requirements presented in section 2.4, construct the basis for this thesis objective. The case is divided into four parts, each representing a possible task for an autonomous robot to acquire from human workers, depicted in figure 4.1. The tasks were chosen based on procedures with most information available in the company document. It should be noted that there are several other possible cases outside those represented below.

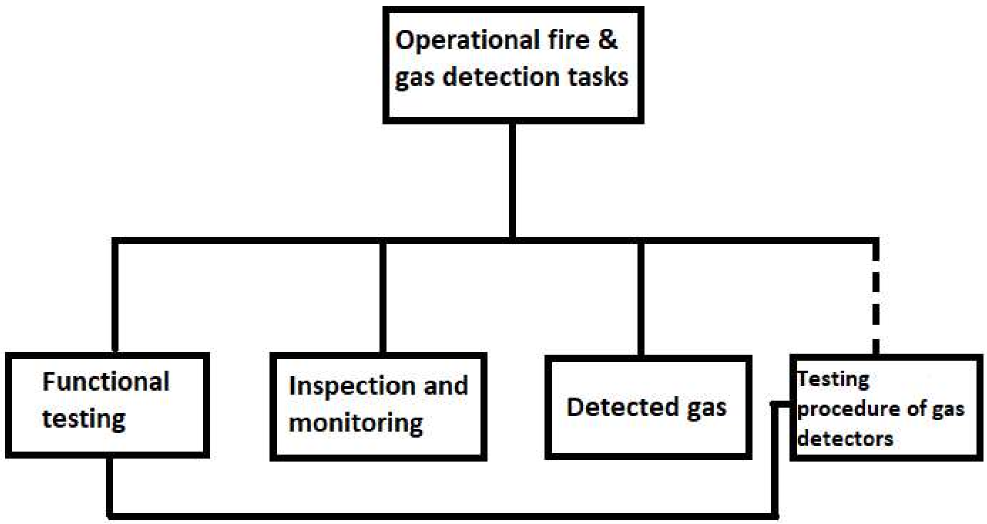


Figure 4.1: An overview of some of the possible tasks to be performed by a robot on an unmanned platform.

4.1 Functional testing

The functional testing procedure supplied by the company is a step-by-step walk-through of eight enumerated bullet points, given in the appendix A1. The objective of functional testing is to verify that fire and gas logic receives alarm signals from detectors.

The testing procedure requires an inspection of field equipment visually. This is well within the scope of a mobile robot. The robot should be able to take pictures and video from many possible angles and heights, assuming that the visual inspection tool is mounted on a movable arm or similar. This requires some thought in design of the unmanned facility, as any fixed detectors must be within the robotic inspection range.

Physical exposure testing requires a robot to perform functional testing on itself and any other fixed detectors. This means the robot should be able to check coverage area (direction and angle), potential coverage, outer soiling, marking etc.

The functional testing procedure relies on verification from a control room. On an unmanned platform this aspect has to change from a control room verification to a robot verification. The goal must be that the robot is trusted enough to perform this task without human intervention. Albeit, there should be a live feed such that a control room onshore can watch as inspection and testing is performed. Another possibility that must be considered is intervention, taking over the robot, using it as an ROV from land. This makes the importance of communication between offshore and onshore vital.

NORSOK states that IR detector response time should be less than 5 seconds, and acoustic detector response time should not exceed 30 seconds. These are acceptable demands, as the robot can signal if response times are too slow. Operators might have to make a decision if this demands a response, sending personnel to the facility for corrections.

Checking that process values are normal can be done by image processing where the robot has stored images of correct placement as a reference. The robot compares the gas meter position from stored images with the one registered live, signaling if the meter is not at a proper position. Ideally, a digital database exists where the robot can access information on gas meters and response times. It may also be possible to have the robot and a fixed sensor both read off the same gas valve, letting the robot calibrate itself through its own data points, along with the sensor readings, comparing measurements.

A proposed adapted procedure could be:

- The robot inspects field equipment visually, looking for potential coverage and other anomalies along a set path.
- The robot performs a physical exposure on its own detection equipment.

- The robot verifies that all its detection equipment is functional, and all alarm levels are activated.
- The robot controls that the response time is acceptable and in accordance with set limits.
- The robot controls that process values are within normal operational values. This procedure is included in 4.3 as a potential task during an inspection round.

4.1.1 proceeds more into detail on how a functional testing procedure is performed.

4.1.1 Testing of gas detectors

As many of the stages for testing of point and line gas detectors are similar, the line gas detector testing has been exemplified. The testing procedure for line gas detectors is given in the appendix.

To indicate low and high alarms, the robot should use a form of self-diagnostics. This can be done by releasing a test gas kept in a small container placed on the robot. Alternatively, there could be designed a test station onto the facility. This station needs to be placed away from explosion zones to protect the integrity of the test chamber, as there would be stored gas containers inside the station. The thought behind this is for the robot to roll into the station and connect to a docking station, letting the system know it is in place. This might be a viable option as the robot might not be able to carry all equipment due to weight and size issues.

As with function testing, onsite CCR will be removed, giving the robot the task of ensuring that a necessary combination of detectors yields confirmed detection. This means that a robotic solution will challenge the voting principles set by government and company regulations. The Company procedure states that alarms from two or more gas detectors must be activated, and minimum one of these must be in high alarm. A possibility is either to double up on gas detectors mounted on the robot, or combine robot detection with fixed gas sensors.

Self-diagnostics could be used to control that detectors are correctly assembled, and can detect potential damage on equipment. I.e. the visual camera must be able to inspect the gas detector, to turn 360°, and change elevation. To ensure that the visual camera is working properly might be a challenge. One solution is to have another fixed camera inspecting, that interacts with personnel off-site overseeing the operation. Making this a bulletproof autonomous operation might be possible in the future, where robots can perform maintenance on other robots.

Controlling TAGs are relevant if detector equipment is designed as a combination of robotic detection with fixed detectors. Meaning the robot can read TAGs off the fixed sensors.

The robot requires a method for cleaning its own sensors. For cleaning of detector optics, a miniature lens wiper could be mounted on the sensor. A cleaning solution can be sprayed on the optics and wiped off by the lens wiper, an idea adapted from car windshields. The lens wiper should be of material able to withstand moisture and salt from the ocean and uphold its function. This can be implemented in planned inspection visits, depending on which maintenance philosophy and type of unmanned platform is chosen. If i.e. the time between maintenance campaigns is below one year, there might not be a need for much cleaning in-between campaigns. However, to increase reliability, there should be a requirement of constant surveillance on visibility for, and performance of, the detector. If the lens wiper should fail, other measures can be considered.

To verify field placement, field layout should be in the cloud and communicated to the robot. The robot can also map the facility itself, comparing the two feeds and signaling if the layout is not according to guidelines.

A proposed adapted procedure could be:

- The detector is activated by release of a test gas included on the robot.
- The robot identifies if the necessary combination of own detection equipment yields confirmed detection.
- Using a visual camera, the robot controls for anomalies or malfunction. Alternatively, every equipment runs a self-diagnostics.
- Control TAG numbers if there are any fixed equipment.
- Self-cleaning of detector optics.
- Do one round through a set path and compare field layout from database with own visual inspection.

4.2 Confirmed gas

The confirmed gas procedure from the appendix A4, states that alarms from two or more gas detectors must be activated, and minimum one of these must be in high alarm. NORSOK states that the role of the detection system is to detect the presence of HC gas, and signal by alarm to initiate safety measures. Section 2.4.1 presented what the standard specifies as actions to be initiated when gas is detected, and is summarized below:

- ESD system is automatically activated upon gas detection.
- ISC is automatically initiated upon gas detection, through actions of the ESD system or can be executed directly by the F&G system.
- Activation of fire water pump start-up and deluge, if required.
- Ventilation is automatically shut down upon gas detection in HVAC inlet.
- Activation of alarm system to alert personnel.

In this section it is chosen to focus on how the robot should respond to confirmed gas.

On an unmanned facility, most or all barriers, deluge system and explosion protection are removed. This means that the immediate steps after a gas leakage is confirmed, are vital to upheld system integrity.

Based on information stated in section 2.4.1, a single sensor mounted on a robot detecting gas may be acceptable. However, the robot might detect gas without any other sensors detecting the same. This means that the robotic sensor must have a failure probability documented as sufficiently low with manageable consequences. Confirmed gas procedures in the appendix A4 states that an ESD is automatically initiated upon detected gas. Uncertainty regarding false alarms inquires if an ESD should initiate if only the robot sensor detects the gas. One possibility is that the robot alerts a remote CCR for verification and initiation of shutdown procedures. As regulations recommend, one detector mounted on the robot might not independently signal an alarm, as there should be a voting in accordance with company and governmental requirements. Ways to achieve a sufficient voting is having more than one inspection robot, additional fixed sensors or more sensors arranged on the robot.

One prospect is to utilize a robot as a first responder to a gas leakage or explosion. This requires a design allowing a robot to move throughout the whole facility. If there are areas the robot can not reach, additional protective barriers should be considered. An aspect relevant to the case is the distance to response personnel. If the robot can not handle the situation, it is important to consider the response time of emergency personnel. Procedures concerning this should be specified in the company inspection and maintenance strategy.

A lot of this depends on the robot communicating with the rest of the platform and it is vital that the communication system is stable. Important questions to consider are: What happens if the communication between systems and the remote control center is disconnected due to i.e. explosion? Is there redundancy? The target is that through continuous inspection, an event such as an explosion should not happen, but there needs to be an assessment of possible outcomes.

4.3 Inspection rounds and reading of instruments

The robot should perform frequent rounds throughout the facility, visually inspecting integrity equipment. For an equally or better performance than fixed sensors, the inspection rounds should be almost continuous. Factors to consider are the length of the inspection route and battery capacity. The robot might need fixed sensors to act as redundancy when the robot is connected to a power supply between inspection rounds.

As a thought experiment, the robot could run along a predetermined path, using thermal imaging and visual inspection to perform certain inspection assignments, as shown in figure 4.2. Step 1 portrayed in the figure, shows the robot scanning the area for anomalies, i.e. finding deteriorating coating or other signs of integrity loss. In step 2, the robot is reading off a gas meter, checking for irregularities in gas pressure, signaling if the picture does not match the robots database. At step 3, the robot detects gas and should follow set procedures, i.e. the procedures stated in the previous section.

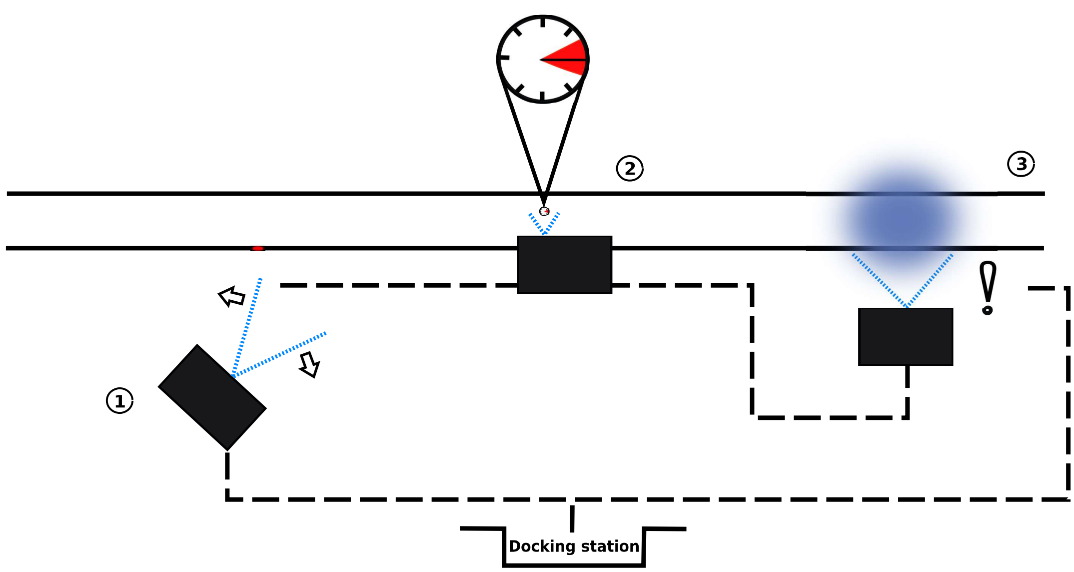


Figure 4.2: An example of an inspection round done by the mobile robot.

A robot could detect a fire earlier than i.e. smoke detectors. By using a thermography camera on inspection routes, changes in temperature can be detected quickly, and either signal for ESD or for remote control to take action. To reach the goal of using an autonomous robot for these tasks, decisions surrounding instigation of ESD, or to signal specialist teams, needs to be decided by the robot itself. Shutdown time should be minimal to save unnecessary expenses, meaning trusting the robot to act correctly will have a large impact.

Using cameras and computer vision algorithms, the images can be processed automatically and the measured values can be reported with a confidence level indicating how good the recording and interpretation was. While instruments provide some information about the operational state and health of the machinery, the equipment can be further examined by the robot using thermal imaging, visual inspection and sound assessment.

4.4 Simulation

There was supposed to be a simulation of an autonomous robot performing the test procedures and inspection presented above, as a proof of concept, but due to causes explained in section 1.4, this was not possible. As some time was put into preparing for this, the imagined simulation and concepts are briefly presented.

The robot was intended to follow a predetermined path from a docking station past certain equipment before returning to base. In the inspection round, the thought was to use thermal imaging snapshots in specific angles as well as reading off gas meters or other instrumentation, sounding alarm to operators onshore if there was any gas detected or other anomalies.

The simulation was to be performed using the Robot Operating System (ROS). ROS is run on Linux and is a middleware for programming robots. The system is open-source and provides many of the same features expected from a standard operating system, including hardware abstraction, low-level device control and implementation of commonly-used functionality [57].

ROS' own website [57] declares that the primary goal of ROS is "to support code reuse in robotics research and development. ROS is a distributed framework of processes, known as nodes, that enables executables to be individually designed and loosely coupled at run time". These processes can be grouped into packages and stacks available to be shared and distributed. Further, the website states that "ROS also supports a federated system of code repositories that enable collaboration to be distributed". This design, using ROS infrastructure tools, enables independent decisions concerning development and implementation to be brought together.

Gazebo is an open-source robot simulator providing a physics engine, 3D graphics and easy communication with ROS through a dedicated node. The ROS-integration means that objects inside the simulation can be manipulated by sending messages from other ROS nodes to the Gazebo node. The Gazebo simulator allows for a "digital twin". A virtual model of the real environment can be simulated in Gazebo. One can either import CAD models or build the world inside Gazebo. This allows for rapid testing during development and can be used for monitoring when the system is up and running. New tasks can initially be simulated before they are initiated in the real world.

For further information, both the ROS website [57] and Nesland [58] gives a deeper insight into the mechanisms of ROS and Gazebo.

4.5 PSA Norway cases

It is of interest to investigate what could have been done differently in the cases audited in section 2.5 if a robot was implemented and the facility was unmanned. Furthermore it is alluring to probe if the cases are relatable to an unmanned approach, and if it results in better avoidance of irregularities. The case problems are somewhat different than those a robot on an unmanned platform would encounter, however, there are some points to consider, further explained below.

4.5.1 Åsgard A

If Åsgard A was an unmanned production ship, it could yield similar condition as a robot would expect. Problems related to F&G regulations on Åsgard A were the fixed fire-fighting systems and gas detection. Fixed fire-fighting systems will most likely not be present on an unmanned platform, making this a task for the robot, if at all.

The report stated that gas detection was inferior during weather conditions such as snow and rain. To secure rapid and reliable detection, sensors should be placed on the robot which will maintain its own equipment. There was no procedure to shut down production and depressurize during these events. This procedure should be strategized in the maintenance plan. In the far future, this decision could be made by the inspection robot.

4.5.2 Ula

On Ula, there was an inadequate ability to reliably detect gas rapidly. It was experienced frequent events with fault detection resulting in fault alarms from line gas detectors leading to an operator having to go out in the field to check for alarm causes.

In this problem framework, the operator will be replaced by a robot. If the line gas detector is placed on the robot, there should be performed self-diagnostics. Either the robot could fix the problem itself, or as a worst case scenario, specialist must be called to the site to perform corrections or maintenance on relevant sensors.

The problem concerning evacuation within five minutes will, during normal operations, not be an issue. However, there should be an evacuation plan for personnel during planned maintenance activities.

4.5.3 Ivar Aasen

The fire and gas detection system could not perform intended functions independent of other systems. This was due to the F&G system and ESD system being interconnected in a network for control and safety systems. Further, the company did not follow voting regulations from NORSOK, stating that the company safety strategy described a voting principle of 2oo2 for gas detectors. This shows a lack of redundancy in the company systems. However, the NORSOK regulations might change when gas detectors mounted on robotics are more widely used. A solution where the F&G system can act independently of other systems should be considered, as previously mentioned in this thesis.

4.5.4 Mongstad

As this audit was not very specific regarding inadequate gas detection, it is difficult to assess this particular case. However, the audit does state that parts of the facility lacked gas detection completely.

The gas leak occurred after an operator tried to operate a valve. This is a procedure that is highly relevant to relocate to an autonomous robot. To facilitate this transition, suppliers must unite to deliver standardized valves that can be operated by a robotic arm, without the need to modify design for each facility.

Detection gear that can detect corrosion under insulation, such as ultrasonic testing or radiography, should be considered when assigning work tasks to the mobile robot. It should be noted that detection techniques such as eddy current might interfere with the robot due to magnetism.

Chapter 5

Facility and robotic design analysis

In this chapter it will be discussed which detection technologies are best fitted to stay on an unmanned facility. Furthermore, which sensor equipment are best fitted on an autonomous mobile robot is investigated.

Additionally, the robotics from the industry, reviewed in section 3.1, and possible improvements on robotic design to perform operational task at high level, is debated. Included in this section are discussions on autonomy and navigational ability. Further, design implication connected to the study cases from the previous chapter are discussed, culminating in a choice of which robotic design solution has the most potential for F&G detection on an unmanned facility.

5.1 Unmanned facility design

Unmanned facilities could be a safer option to contemporary manned facilities. Concentrated areas of personnel such as offshore installations with living quarters, offices or transportation, are potential places where an incident may result in considerable life loss.

The majority of incidents seems to occur due to inadequate system integrity, such as leaks or mechanical failures.

Although daily operations are unmanned, there should exist a specialist team onshore dedicated to operation and maintenance of the unmanned facility, whom are familiar with the installation, and can be mobilized if an event occurs. Throughout the project development there should be focus on creating a strategy that clarifies time between manned maintenance operations, and which tasks requires manned intervention.

Designing an unmanned facility is quite disparate from a conventional development project. In a conventional project, proof must be given to authorities that the facility has been adequately designed for safety. On an unmanned facility, extra equipment not vital for the daily operation must be avoided. I.e. HSE elements might be attached, out of habit or as a “just in case” scenario. These types of equipment does not add any significant value, requiring a higher manning frequency because of more safety equipment inspections.

However, maintenance personnel might get injured on the facility if it is not fully bled down before arrival. According to Nolan [9], most incidents occurs during periods of maintenance activities, start-up or shutdown. This means that periods with maintenance is the stage when more attention, knowledge, and experience are required from personnel to safely manage the facility. If there is an ongoing event when the specialist team arrives, there needs to be set procedures.

With no barriers or safety equipment available, new approaches are needed to ensure facility integrity. One possibility is to include a designated maintenance robot with more specific equipment controlling it from a distance much like a bomb disposal robot. There could also be placed a temporary refuge, where personnel can take refuge for a predetermined period while investigations and emergency response are undertaken. Another possibility is to use the robot already on site. The robot can be fitted to do maintenance tasks, assuming it is built with modular gear that can be attached on and off depending on task requirement.

Campaigns, and the majority of required manned operations on the unmanned facility should take place during the summer time, when weather conditions are easier to predict. Important factors to consider are distance to host facility or onshore control, reservoir complexity and frequency of well interventions, and the need for operator interventions and maintenance requirements. Unmanned robotics will spare a substantial amount of manning hours. Additionally, it can increase efficiency during maintenance campaigns, assisting with operations and safety aspects.

Based on the information gathered in the pre-study [1] and section 3.2, the amount of equipment and systems on an unmanned facility should be minimized, keeping only equipment with with high reliability and robust materials. This will reduce capital and operational expenditures. Remarks and discussion in this section yields a conclusion that a type 2 or type 3 unmanned facility are preferred concepts, maybe even a type 4 if the facility is connected to a host facility nearby. The earliest unmanned facilities might choose a type 2, which facilitates a crane, but no fire water or process facilities, mostly chosen because of an unmanned operational window for periods of 3-5 weeks. Ideally, a type 3 unmanned platform should be the goal, with an unmanned operation for periods of 6 months to 2 years. The preferred access method is a W2W bridge. The W2W bridges can become the future method of access to unmanned facilities provided that there is a sufficient availability of vessels with W2W bridges installed.

5.2 Choice of detection equipment

As F&G detection equipment should stay on a facility without human intervention for perhaps half a year, the sensors needs to be robust, stable, reliable, have good self-diagnostics and little to no degradation over time. These are tough criteria, but to successfully integrate F&G sensors on an unmanned facility, it is important to choose the right technology. Presented in table 5.1 are some of the pros and cons for each gas detection technology.

According to NORSOK, open path detectors should be preferred where possible, and open path should be used in combination with point detectors where environmental factors may

Table 5.1: Some of the advantages and disadvantages concerning gas detection technologies.

Detection technology	**Advantages**	**Disadvantages**
Catalytic	Simple and inexpensive. Robust. Wide temperature range.	Gas contamination. Degradation of sensor. Needs calibration often. Long response time.
Point IR	Factory calibrated. Can operate continuously in presence of gas. Immunity to contamination.	Physical gas contact needed. Gas must absorb IR energy. Not good for multiple gases
Line/ Open path IR	Good stability over time. Can monitor large areas. Immunity to contamination	Physical gas contact needed. Requires no obstruction of beam path. Gas must absorb IR energy
Acoustic	No physical contact. Little impact from weather conditions. High sensitivity. Good self-diagnostics.	Only detects leaks in ultrasonic range. Requires establishment of background noise to set alarm level. Prone to false alarm.
Optical	Fast response time Can withstand harsh weather conditions Good self-diagnostics.	High cost. Fault if condensation on lens.
Electrochemical	Fast Response. High accuracy. Versatile.	Limited to low temperatures. Narrow range of pressures. No fail-safe.

make open path detection unavailable. Further, the standard suggest that catalytic detectors shall not be used unless proper detection by other types is not achieved.

Catalytic detectors are ruled out, as the disadvantages presented in table 5.1 are incompatible with an unmanned maintenance philosophy. The need for calibration often, as well as a degradation of the sensor over time will lead to much uncertainty. How often this is the situation is not specified, but the risk of a system failure is deemed to high.

Acoustic detectors have a high sensitivity, catching small gas leakages other sensors might overlook. As the detector has good self-diagnostics and are not heavily affected by weather conditions, it can be used either separately or in combination with gas concentration sensors or IR cameras.

IR detectors has a high degree of self-diagnostics and are usually tested once a year, fitting the profile of an unmanned facility. Sensor fault or failure are continuously monitored and the detector is factory calibrated. NORSOK's recommendation influences the decision of using open path IR detectors over IR point gas detectors. However, figure 2.7 shows that this type of detector needs both a transmitter and a receiver. Meaning the robot will need to point its transmitter on set receiver throughout the facility. In conclusion, IR cameras will be able to detect i.e. a gas leak better than humans, and should thus be implemented as soon as possible to assist mounted gas sensors.

Optical detectors might be too expensive. The combination of fast response time, being able to stand against harsh weather and good self-diagnostics are vital on an unmanned platform, making it recommended if economically viable. Such a detector should be compatible on a robot as well - if there are issues with condensation or water on the lens, worsening its effect, the lens wiper method presented in section 4.1.1 might be a possibility.

The operational window for optical detectors is relatively large, but might lose some of its functionality if snow, fog or steam occurs. If a gas leakage arise during such conditions, the detectors might not be able to detect the gas. To compensate it could be possible to use specially adapted logic, use other detectors or improve current detector design. A traditional IR detector could have problems identifying one particular gas among multiple gases and therefore also gas concentration. A laser detector has other combinations of wavelengths, coinciding with absorption that are characteristic of a particular gas.

Electrochemical detectors, like catalytic detectors, can be inhibited by small impurities affecting the sensing and detection ability. They have no fail-safe and a small temperature-range. Even though some of the upsides presented in table 5.1 are favorable on an unmanned facility, the limitations excludes the technology for this thesis objective.

The reliability of a gas detectors depends on both the detector, how the detector is adapted for use, which functionality the detector has and how it is integrated with other detectors in the SIS. Independent of detection technology, the variation in placement and height of detectors as well as geometry and direction of gas release, will affect response times. If an area is not instantaneously filled with gas, the detector response will vary dependent on placement in proportion to leakage source. This leads to the conclusion that no single detector technology or type is robust enough to provide the sensitivity and fast response time required for every gas. Some of the obstacles concerning placement and response time might be eased by implementation on a mobile robot, this will be discussed further in section 5.3.

NORSOK [29] states “Dispersion simulations may be performed for optimisation of the number and location of detectors”. Operators use both simulations, 3D modeling and manual analysis of layout. Even advanced modeling and simulations has issues optimizing detector placement when taking into account explosion pressure, potential gas leaks, gas concentration and possible wind conditions. Unmanned facilities are more compact as well, making modeling even harder. Nesland [58] states that ideally, a 3D vision system should be used. This is because it would allow the robot to estimate the position of the leakage in the frame of the map, not only in the image plane. Another solution could be to make the robot take pictures of the same leakage from different positions and calculate the depth based on two images and the two corresponding robot poses.

Several technologies are applicable for an mobile inspection robot. There should be an IR camera mounted on the robot, as well as a camera for visual inspection. In addition, a laser detector would suit the assignments found on an unmanned facility. To cover a broader spectrum there should be an acoustic sensor for measuring of sound waves. Another inspection tool that could be useful is a flashlight in case of enclosures around equipment. While redundant detectors and the other special features discussed above may increase the cost of an F&G system, the payoff is a complete system that effectively protects a facility from fire and explosion risks.

5.3 Robotic use-cases

Firstly, a mapping of use cases for a robot detection seems beneficial. From the pre-study [1] it can be deduced that robotics can be utilized to detect degradation in valves and rotating equipment. One interview subject stated that half of the maintenance hours goes to scheduled maintenance, and almost all of this on EX control, testing of safety functions and certifications. Further, it was concluded that inspection will be the main task of the robot. It should search for anomalies like gas leakages, and may even be used for cleaning tasks. A robot equipped with a rotational manipulator will have extended use-cases. It will allow the robot to move equipment, and even open and close valves if the actuator fails. The robot could also apply techniques to assess the status of the coating by measuring its thickness, while a visual camera records the external surface to detect loss of coating. Detection of corrosion and internal defects like cracks is also required.

It is important to keep in mind that the maintenance tasks mentioned will not be feasible until facility equipment has a standardized design. This is not practical on an existing manned platform, but preferably the unmanned facility will obtain a standardized and modular design, making it easier for the robot to change parts.

Pfeiffer et al. [46] states that a robot should autonomously perform inspection and maintenance tasks such as monitoring of gauges and meters, visually inspect remotely operated valves, acoustic inspection, and leakage monitoring. This coincides well with knowledge gained from this thesis. The robot operation is focused on teaching the robot to execute tasks, autonomously carrying out the taught sequences, while remote operation is also possible.

5.4 Robotic design

Although the reliability of the detectors themselves may be high, detectors can detect only incidents that their sensing mechanisms can access. Gas detectors can detect only the gas that reaches the sensor, dead spots and other related effects give a practical limit to achievable detection performance. The goal of the robotic design should be to achieve reliable detection of F&G despite limitations.

5.4.1 Navigability design

A mobile offshore inspection robot needs to be able to navigate safely in offshore environments. Which design that are preferable depends on how the facility is designed. If there are several levels on the facility, having a robot stationed at each level could be an option. If the option is deemed too costly, a robot with the ability to navigate between levels should be considered. However, if the determined inspections path is too long, yielding worse detection than fixed sensors, as a gas leak might develop for some time before the robot returns.

If there are obstacles on the facility, the robot can take photos of all found obstacles after a successful inspection route, implementing a new path steering clear. If a manipulator is implemented, the robot could remove potential obstacles.

Carvalho et al. [48] proclaims that the use of a rail mitigates several issues such as motion, obstacle avoidance, planning, localization and mapping. A rail-guided robot will avoid collision with equipment and people, due to its controlled motion and constrained workspace. In addition, a predefined path complies with the routine inspection tasks of the robot. However, this solution yields less freedom, with limited improvisation and no possibility to manipulate the environment.

One option is to employ legs as a trampling method. Gehring et al. [49] states that their robot with legs autonomously performed various inspection tasks and navigated over difficult terrain including stairs. Further, it is stated that “To navigate through the environment, the robot uses perception sensors to localize itself in the environment and to avoid obstacles”. The robot also used different speeds depending on terrain, slowing down on more challenging ground. This proof of concept makes it a viable option.

The Taurob Tracker has shown proficiency dealing with obstacles as i.e. staircases [1]. A crawler handles wet or slippery surfaces better than a legged robot without investing heavily in materials. Furthermore, it is not bounded by a rail, letting it move more freely. On the other hand, a crawler might not easily fit everywhere as it will be more bulky and heavy compared to other designs.

A robot on wheels will have difficulties with stairs or other height obstacles. One solution is to design the facility to include i.e. ramps instead of stairs or keep all equipment on one level. Facilitating this sort of robot might lead to unnecessary expenses. Drones have not been targeted specifically in this thesis, as they will be able to carry much less equipment, and are quite prone to poor weather conditions.

5.4.2 Autonomy

The robot needs to make decisions by its own accord, including navigation and detection. This requires a lot of training scenarios to make the robot recognize possible situations. Further, it is important that the robot recognizes some fundamentals when an unknown situation occurs. The cases reviewed in section 3.1 shows that autonomous inspection is a possibility. I.e. [46, 48, 49] were successful completing inspection or navigation tasks autonomously when deployed on an offshore facility.

Nesland states that "Autonomous operation is necessary to minimize the need for human intervention and thus increasing the efficiency". Autonomously navigating throughout the facility requires the robot to find its own position, plan a path and move along it while avoiding collision. Predefined inspection routes can be programmed to control that normal operation is maintained, like in the example from section 4.3. If deviations are found, the robot needs either to instigate a damage limiting procedure, or alert remote operators. The robot can use image classification techniques to automatically detect failures, processing this to remote operators. In the future, the prospect is that an artificial intelligence could be strong enough to take action if provided the necessary tools.

In the starting phase of using mobile robotics on unmanned facilities, it might be worth considering a semi-autonomous approach. Remote operation where humans can control robot modules makes the system more flexible, and able to perform tasks that are not pre-programmed. It is also paramount to have redundancy if the robot's autonomous operation cease to function. The visual camera mounted on the robot could be used as a tool for operators to navigate the unmanned facility.

5.4.3 Impact resilience

Since the facility should stay unmanned for up to 2 years, all equipment must be reliable and robust. Nevertheless, EX proofing the entire facility will drastically increase expenses.

Furthering on the robot as a first responder - the robot must be EX proof, staying intact during an event in order to alert onshore control of the situation. The material must be able to protect sensor equipment, i.e. a protective hood surrounding the equipment, or use sensors that are certified to withstand an EX. Another opportunity is to use an open/close mechanism, shielding the equipment when not in use.

As fire water systems are discarded, the robot could be assigned to work with fire limitation. It is not realistic for the robot to act as a fire truck, but it might be able to manoeuvre a fire extinguisher. Further, the maintenance plan should assemble a procedure for handling of catastrophic events, stating if the facility should burn down in case of EX or fire. In any case, the most effective way to limit escalation and damage is to detect and control fires at an early stage.

If communication systems are nonfunctional as a result of an EX, the robot needs to be aware that its not communicating with other systems anymore. One solution could be to have a redundant communication system, i.e. placed near the robot docking station. This concept relies on the docking station keeping integrity during an event, upholding the power supply. If the power supply is subdued, there is a need for backup batteries and possibly a long distance network gear mounted on the robot, independent of other systems. The upside is higher reliability and robustness, albeit somewhat immoderate.

5.4.4 Structure

There is no standard for robotics topside in the oil and gas industry. Standards exists for automation, control and tele-com, safety, cyber security and other disciplines. Due to this fact, many different types of robotic solutions are viable, as there is a larger freedom to choose a layout.

The base of the robot can employ a modular structure. One side could embed all the electronics and power supply systems, including connection tools for a docking station and batteries. Another module could yield the manipulator arm with some sensors equipped, and one module comprising of further sensing devices.

An actuated manipulator arm increases the workspace of the inspection sensors, as the cameras can be aligned to the inspection targets independently of the robot's position. The manipulator should be low weight due to traction limits, and be able to retract to a compact position when it is in standby mode, to not interfere with facility equipment. A modular and reconfigurable manipulator are useful tools if equipment must be replaced based on testing, inspection or maintenance task at hand. This is particularly convenient if the robot needs to expand to reach certain areas or accommodate more equipment. A manipulator could be used if there are multiple robots on the platform. If one robot is stuck, or runs out of battery, another robot can use the manipulator to help the stranded robot back in service.

As stated in section 5.2, an IR camera, several visual cameras, a laser detector, a flashlight, and an acoustic sensor are equipment useful for F&G detection. Additionally, navigation sensors should be placed around the robot structure. In case of obstacles on the pre-determined inspection path, the robot could have a safety bumper to hinder a collision, potentially destroying the robot or facility modules.

5.5 Robotic solution

Performing F&G testing, inspection and maintenance tasks required of an autonomous mobile robot on an unmanned facility has been the basis for the proposed robotic solution. A sketch of an ideal robotic design is given in figure 5.1. This sketch is based on design criteria and considerations presented in this thesis, minding important factors for a robot to successfully operate on an unmanned facility over long periods of time.

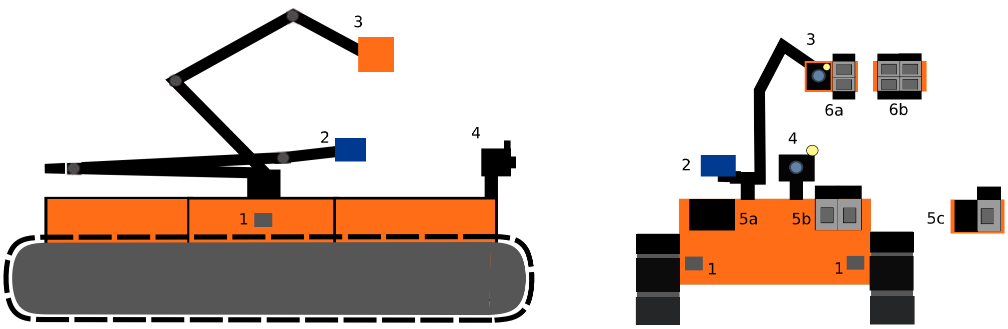


Figure 5.1: A proposed robotic design

Number 1 shows three of the six navigation cameras, one at each side, and two at the front and back. These are set in the housing to avoid any obstacles in the path, and placed at a height where it is possible to monitor the moving belt. Number 2 and 3 depicts the two manipulator arms. The orange arm is used for inspection, the blue is designed for future maintenance tasks. The maintenance arm should support a modular approach, with i.e. a gripping claw as the basic equipment. It is also possible to change the layout to use only one arm, however this design secures that there are no sensor downtime. Number 4 shows a visual camera with flashlight, and has the possibility to move around 360°for inspection of the robots own equipment. Number 5(a,b) are places where other inspection tools can be placed, where EX proofed cover can be attached, and opened/closed whenever the equipment is needed. Number 5c shows when one cover is open and the other closed. In this case, the inspection tools would be an acoustic sensor and possible several IR or visual cameras, as well as a laser detector. Further, as shown in the figure, there are several possible design options for the inspection arm. Number 6(a,b) shows an IR camera for thermal inspection mounted on the inspection arm. Additionally, a visual camera and a flashlight should be mounted on the arm. Finally, equipment for charging at designated docks should be integrated in the rear end of the robot.

An important factor to consider is that all cases presented in chapter 4 should be successfully performed for the design to be viable. These are work tasks that are essential. With this design, performance of functional testing and gas detector testing should be realizable. I.e. a test gas can be placed at 5b in figure 5.1 to perform functional self-testing. Further, the robot should be able to perform the inspection round shown in figure 4.2 successfully. One downside might be the size of the robot construction. Fitting this amount of equipment on a mobile unit leads to a heavy and bulky appearance. This means that some equipment might have to be discarded in order to fit the facility inspection paths.

Based on the assessment of design criteria in this chapter, the Taurob Tracker is closest to an ideal design. The system is equipped with multiple cameras, in order to transfer live images. One camera at the front and rear in the housing respectively, as well as various optional cameras on the arm. LED lights ensuring good illumination in darkness. At the end of the arm is an optional gripper or a retainer for measuring devices. The possibility to mount several optional cameras on the arm is a feature that can be exploited, matching the sensor layout with the proposed solution.

It should be possible to adapt the Taurob tracker to conform with the findings in this thesis, as all the tools are readily provided. Regarding navigation, the Taurob tracker has been shown to be able to overcome obstacles as staircases [1]. This means it should have no problems with handling numerous different facility layouts. EX equipment does not function well when applied to drones, yielding lesser performance because of weight, losing a lot of the benefits from using a drone. With crawlers the situation is different, as weight is not an issue to the same extent.

Taurob is not autonomously run at the moment, but this software could be implemented at a later stage. Making the robot EX proof should be a consideration if it is chosen for use on unmanned facilities. The robot also needs to be fitted to a possible docking station and integrated for remote operations.

Chapter 6

Conclusion

This thesis has mapped detectors feasible for F&G detection, and investigated how choice of detectors, installation, layout and requirements and regulations affects the choice of a robotic solution. The literature review assessed possibilities for unmanned offshore topside platforms. Further, sensor selection and robotic design has been discussed.

It has been found that robotic inspection can lead to time and costs savings in terms of manned operating hours and transport resources. Robotics will yield faster detection of leaks, minimizing exposure and risk to the facility or maintenance personnel. During emergency operations, a robot could be deployed to investigate sources of leaks, reducing or eliminating human intervention.

It has been performed a study on changing test procedures concerning F&G detection from a manned to a robotic perspective. It was concluded with an appropriate robotic solution, adequately performing assigned testing, inspection and maintenance tasks on an unmanned facility. Sensor equipment chosen for use on the robot are IR cameras, visual cameras, acoustic sensors and laser detectors. This combination of equipment yields an adequate detection range. Both robot and facility equipment should be designed modular, with parts easily replaced or modified.

6.1 Further work

Based on the discussion in chapter 5, possibilities for future work can be summed up to:

- There should be a standardization of unmanned facility equipment. A opportunity is to study how this could be possible to implement.
- The robot design should be tested on a relevant industrial site over time, to weed out any irregularities.
- A real life case-proofing of the robotic solution in section 5.5.
- A study into EX materials relevant for offshore robotics.
- Experimental testing of procedures from chapter 4
- A cost analysis for the fully equipped robot, comparing it to cost of personnel and manned operations.

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Appendix - Maintenance philosophy on facility X

Generally, all equipment should be subject to a standardized maintenance concept, to ensure that testing and maintenance is done in the same fashion, after the same standard, across the whole company.

A1 - Functional testing

The objective is to verify that fire and gas logic receives alarm signals from detectors. This is done through physical exposure of the detectors to reveal possible hidden errors. All detectors are subject to testing. The execution procedure is:

1. To reveal undetectable failures, the system is tested before calibration and cleaning.
2. Fixed equipment that can be a cause of failure should not be dismantled during testing.
3. Inspect field equipment visually. Check coverage area (direction and angle), potential coverage, outer soiling, marking etc.
4. Perform physical exposure of all relevant detectors. All alarm levels are activated.
5. Verify, in a control room, that all locations and statuses on detectors are correct.
6. Verify that the response time is acceptable and as expected for that type of field equipment.
7. Before a reset, it must be verified with the control room that no one else are using the same overriding/bypassing and disconnections.
8. Process values must be within normal operational values, and all alarms signed for, before the fire & gas system can be reset.

A2 - General requirements

The fire area must be cleared for testing before detectors are activated. Only one area can be tested at a time so that active bypassing are reduced to a minimum. Field personnel does not need to keep track of which detector that are being tested. Testing is documented by marking it in the F&G test folder by CCR, CCR has overview of which detectors that remains. Field personnel inform the TAG to CCR, to control that the necessary bypassing is done in CCR, before a detector is activated. CCR clears that the detector can be activated. Responsible for test and execution in field is the ”executing specialist unit”.

Failure definition

For flame, smoke and heat detectors and manual alerts, the failure definition is: The fire and gas logic does not receive an alarm signal when using the prescribed test method.

For gas detectors (IR, catalytic, electrochemical, acoustic), the failure definition is: The fire and gas logic does not receive a signal equivalent upper alarm limit when using the prescribed test method.

Test interval

There was an initial requirement of a maximum test interval of 12 months on all detectors and logic. For catalytic gas detectors the requirement is 6 months. IEC 61508/61511 opens for re-evaluation of test intervals based on experience with the equipment. Detectors now have generally a 24 months test interval, with some exceptions, i.e. H_2 detection and inside turbines.

Requirements and voting

- Gas point detector

  Low alarm: Indication > 20 % LEL

  High alarm: Indication > 30 % LEL

- Gas line detector

  Low alarm: indication > 1 LEL$_m$

  High alarm: Indication > 1.5 LEL$_m$

- Air intake

  Low alarm: Indication > 5 % LEL

  High alarm: Indication > 10 % LEL

Alarms from two or more gas detectors must be activated, and minimum one of these must be in high alarm. There is no distinction of line- and point detectors, meaning they are voted together. Flame detectors has no warning alarm, only High-High alarm. For a confirmed detection, an alarm from two or more flame detectors must be activated.

A3 - Test procedure of line gas detectors

The detector is activated with a test-sheet for indication of low alarm and high alarm. There is no specific LEL value on the test sheets. Start i.e. with a B-sheet to get a low alarm and then gradually increase the strength to achieve a high alarm. CCR makes sure that the necessary combination of detectors yields confirmed detection. Control the detector with associated cable for correct assembly and potential damage. Control TAG numbers on detector and cable. Clean detector optics (both transmitter and receiver). Verify that field placement is according to the F&G layout and that the module description is correct and following the Fire Protection Data Sheet (FPDS).

Test procedure for point gas detectors

The detector should be activated with the same test gas (50% LEL) for indication of both low alarm and high alarm. Normally, 4 L/min is usually sufficient, but can be affected by high wind speeds. If the detector is equipped with a permanent test tube, remember to blow the tube after testing. Control the detector with associated cable for correct assembly and potential damage. Control TAG numbers on detector and cable. The detector shall be reported as fault if it does not supersede 50 % with 50 % LEL test gas. Point gas detectors is not normally cleaned on preventive maintenance. If bad response, it should be cleaned. If it is outside of ± 3 % LEL when there is no gas present, it should be cleaned. Verify that field placement is according to the F&G layout and that the module description is correct and following the FPDS.

Testing of flame detectors

The detector is activated by a magnet. CCR ensures that necessary combinations of detectors yields a confirmed detection. Control the detector with associated cable for correct assembly and potential damage. Control TAG numbers on detector and cable. Detector optics should be cleaned after activation. The detector should be set so it covers the zone that is projected on screen in CCR, as well as being in accordance with the F&G layout and that the module description is correct and following the FPDS.

A4 - Testing of confirmed detection

1. Let a random detector lay unacknowledged in alarm. Check that it is still on alarm.
2. Executing enables a new detector in the same area.
3. Check that confirmed actions are set.
4. Acknowledge and reset when the detectors are normal.
5. Put outputs back to normal when all inputs and outputs are checked and there are no actions.
6. Turn off the connection for the area when the test is paused or has ended.

Contact automation immediately if there is any failures.

Christoffer Grytøyr

Design Implications for Robotized Testing and Inspections of Fire and Gas Detectors

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