UiT The Arctic University of Norway

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Continuous Autonomous UAV Inspection for FPSO vessels

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Summary

This Master's thesis represents the preliminary design study and proposes the unmanned aerial vehicle (UAV) -based inspection framework, comprising several multirotors with automatic charging and deployment for 24/7 integrity inspection tasks. This project has three main topics. First one describes the operational environment and existing regulations that cover use of UAVs. It forms the basis for proposal of the relevant use-case scenarios. Third part comprises two chapters, where design of concept and framework is being based on the previous factors. It shows that before implementation of fully autonomous inspection system, there is a need to cover both regulatory and technical gaps. It can be explained by the fact that there does not exist any autonomous inspection system today. Thus, this project can be seen as a base for future development of the UAV-based inspection system, as it focuses on creation of a general framework.

Preface

This thesis is submitted as the partial fulfillment of the requirements for the Master's degree in Aerospace Control Engineering at the UiT – The Arctic University of Norway. The project is based on the assignment proposed by Equinor ASA during the spring of 2021.

I would like to thank my main supervisor, Prof. Raymond Kristiansen, for his valuable advice and regular support. I would also thank Marius Paulsen Haugen and Roy Ivar Nielsen at Equinor ASA dep. Harstad for their support and help when needed. All of you have provided the positive working environment and interest you have shown for my work helped me to keep inspiration throughout the project.

Special thanks go to my mother, grandmother and brothers. I would never be where I am today without your support.

Report outline

This thesis is divided into seven chapters. After introductory, where we discuss existing solutions related to autonomous inspection of vessels and opportunities related to the use of robotic arms for inspections and maintenance tasks. In **Chapter 2**, we get an understanding of the environment where all operations will be performed. It also contains some basic requirements for drones and supply infrastructure, discussion about challenges of flying in explosive atmospheres. Based on this information, then in **Chapter 3**, there are proposed possible use-case scenarios which may be relevant to be used at the Johan Castberg vessel. **Chapter 4** proposes the concept prototyping, system architecture and discussion about how to get a fully autonomous system. **Chapter 5** complements with information about fleet configuration and what kind of infrastructure we need in order to get a workable system. **Chapter 6** is based on discussion about the existing regulatory and technological gaps, how they affect use-case scenarios, and what is needed to cover them. Finally, **Chapter 7** describes final conclusions and prospect for future work.

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Abbreviations

AGL	(height) Above ground level
BLOS	Beyond visual line of sight
CG	Center of gravity
DOF	Degree of Freedom
EASA	European Union Aviation Safety Agency
ERT	Emergency response team
EVLOS	Extended visual line of sight
FOV	Field of view
GNSS	Global navigation satellite systems
HFIS	Helicopter flight information service
HLO	Helicopter landing officer
IACS	International Association of Classification Societies
ID	Identification
IR	Infrared
LPS	Local positioning system
MTOM	Maximum takeoff mass
ND-IR	Non-dispersive infrared
NDT	Nondestructive testing
NED	North East Down reference frame
NOTAM	Notice to airman
PAV	Pico air vehicle
PDA	Personal digital assistant (also known as handheld PC)
RMZ	Radio mandatory zone
RPAS	Remotely Piloted Aircraft System
RVI	Remote Visual Inspection
SERA	Standardised European Rules of the Air
SWIR	Short-wave infrared light
UAS	Unmanned aerial systems
UAV	Unmanned aerial vehicle
UUV	Unmanned underwater vehicle
VLOS	Visual line of sight

Acronyms

cat.	category
w/	with

1 Introduction

In the first quarter of the XXI century, when use diverse types of “ecologic-friendly” energy sources, such as solar or wind energy, does not surprise anyone, the oil and gas production is still relevant and plays a significant role.

At the same time Unmanned Aerial Vehicles (UAVs or drones) being also used more in everyday life. They are performing a lot of different types of tasks and vary in complexity of design. Being widely used onshore, they are not that much presented in maritime operations. Even today there still exist both technical and regulatory gaps in activities related to autonomous inspection of the ships.

Oil extraction in arctic sea regions is quite challenging even in our modern days. Workers and machines often work in extreme conditions. To reduce risks and improve efficiency, new drone- and robot technologies are coming for help. Energy industry sets focus on increased use of drones and robotic technologies in different scenarios. Its goal is to increase safety for a crew and increase the production efficiency on the shelves.

1.1 Background and motivation

This project is given in cooperation by University of Tromsø (UiT) and Equinor ASA, and is based on the Preliminary Literature Review project, done in December 2020 [18].

The use of FPSO vessels (Floating Production, Storage and Offloading) in oil and gas production is becoming increasingly popular, enabling offshore handling of all pars of the petroleum extraction processes. These types of vessels are then located close to the oil field for extensive time periods, and must maintain operation in harsh weather conditions. Thus, the need for continuous inspection and maintenance tools is pertinent and required, for which unmanned aerial vehicles (UAVs) can offer a robust and reliable solution. The general objective for this project is therefore to perform preliminary design study into an autonomous UAV inspection framework comprising several multirotors, allowing continuous operation without human intervention, for performing specific inspection tasks on a FPSO vessel.

Subtasks

- Perform a literature review on autonomous drone inspection in general and for FPSO vessels in particular.

- Suggest specific inspection tasks that are suitable for multirotors, and develop some use case scenarios and usability studies. Particular use cases to study is FPSO tank inspection, and the possibility to use drones with gripper arms.

- Based on some of the use cases, suggest a framework comprising several multirotors for continuous inspection, including automatic docking and charging. Take special considerations for robustness requirements for the UAVs, as well as requirements directed by the operating environment (EX requirements), and necessity for supporting infrastructure (positioning, communication).

- Based on the Johan Castberg FPSO, establish a scheme for automatic scheduling, flight logistics and path planning to ensure continuous operation and coverage.

1.2 Project limitations

The idea about how to use unmanned aerial vehicles (UAV) for autonomous inspection of the vessels has been proposed only few years ago. Having a such new field of study creates the first barrier – existence of regulatory and technological gaps, which needs to be covered prior implementation of the system with desired level of autonomy. This resulted in making of some "what if" assumptions and general discussions based on available information.

The autonomous UAV-based inspection system for offshore operations is a complex structure that combines many aspects, ranging from legislation, maritime operations, meteorology, aircraft control, algorithm design, and others. It led to more time spent to get the specific knowledge base, than it was planned initially.

To perform inspections or other tasks on vessels, we can use not only UAVs but also crawling robots or underwater vehicles to inspect areas that are not reachable by UAVs. They could expand the capabilities of the UAVs, but to include them into concept design would require much more additional time. Due to strict time constraints, it was decided to not include them into this project but leave for potential future study.

1.3 Literature review

There already exists a lot of variable solutions for manual drone inspections in multiple civil scenarios [9][19]. It can wary from soil pollution and vegetation monitoring to determination of volatile chemical concentrations and gas leaks detection at chemical plants. It was done many researches so even guidelines for optimal flight path were derived and also ability of different sensors to perform in different light conditions [19][20][21].

When it comes to maritime and oil rig inspection the things become not so bright. According to European Research Project ROBINS (Robotics Technology for Inspection of Ships) [22], done as a part of the European Union's Research and Innovation programme "Horizon 2020" [23], there still exists both technology and regulatory gaps when it comes to the adoption of Robotics and Autonomous Systems (RAS) in maritime inspections. As one of such gaps we can mention navigation inside cargo tanks. According to ROBINS, automated navigation with correct motion estimation is not solved yet for the case of ship inspection [24]. Most of the projects are related to the inspection of cargo holds and tanks (on bulk and oil tankers) only, sometimes they also include inner compartments of the ships [25][26]. There also exists some projects on oil rigs' outer inspection [27][28]. In all these projects, drones were manually controlled by experienced pilots [29]. In all cases, they pointed out weather conditions, namely wind, as the most challenging impact on the drone operation.

Most of the similar projects started in last 2-3 years. The biggest existing project that has been found is the previously mentioned ROBINS project, that started in 2020. Hence, we can see that this line of research is relatively young. So, we will base us on existing solutions that are used for onshore inspections.

Robotic Arms

One of the ways to improve the drone's performance for inspections and to perform the maintenance tasks is to equip them with gripper arms (also called "aerial manipulator" when installed on UAVs). They will not only work for improvement of the performance but will also allow to sense in difficult to reach or dangerous zones.

The aerial manipulators can perform variety types of tasks. It can be simple "grasp-and-transport" [30], cable-suspended load lifting [31], remote opening of valves [32], or more advanced and complicated as structure maintenance using several manipulators installed on one drone, which being developed under AEROARMS project [33].

More often such manipulators are used to perform nondestructive testing of different constructions, such as bridge beams [34], ultrasonic thickness measurement of oil refinery [35]. In marine inspections usually we do not need to use all available inspection techniques (sensors) simultaneously. So having few detachable end effectors can save in drone's weight and thus get longer flight time. It will also make sensor's service or replacement easier.

We can divide robotic arms into several groups, based on several factors. The most common one is by their working principal [36]:

- Vacuum
- Pneumatic
- Hydraulic
- Servo-electric

Another way, is by the end-effector type [37]:

- Gripper - they are also divided into subgroups:
  - Multi-finger adaptive;
  - Parallel Motion Jaw
  - Claw
- Process Tools
- Sensors

Because of its small weight and no use of liquids/oils nor compressors, probably the most suitable type of end effector is servo-electric.

The problem, or challenge, of the aerial manipulator usage is in complexity of the kinematics and control[38] due to coupling of the manipulator's- and drone's dynamics. The challenge of the aerial manipulator usage is in complexity of the kinematics and control [38] due to dynamics of the coupling of the manipulator with drone. There are three effects that complicate behavior of the drone with attached manipulator [39]:

- Displacement of the mass center from the drone's vertical axis
- Variation of the mass distribution during arm manipulation
- Additional dynamic forces and torques that occurs during arm manipulations.

This problem can be simplified by using manipulators with less DOF (2, 3 or 4). It will decrease mobility of the arm and will need the compensation in form of horizontal/vertical movement of the drone, and still manipulator will be dependent on the attitude of the UAV. Such simplification can be used during NDT (Non-Destructive Testing) tests inside an oil/ballast tanks, but for outer surveys we will need the more freely movable arm, which has at least 6 DOF. Because the vessel is in constant movement about its axes and due to varying weather conditions, it is necessary for the drone to be able to actively compensate it. Another solution is to use drones that have electromagnets to “stick” to the surface, have tilting rotors or one additional rotor to “press” drone against the surface to hold it in place.

2 Operating Environment and Basic Requirements

2.1 Johan Castberg oil field

The focus for this project is the Johan Castberg oil field. It is located in southwest part of the Barents Sea, 240 km north from Hammerfest in Norway, as can be seen in Figure 1. The Johan Castberg field includes three oil reservoirs: Skrugard, Havis and Drivis. According to the plans of the Equinor [40], the extraction of the crude oil and gas will start in 2023 and last for 30 years. The expected volume of the extracted resources is equal to 450 – 650 million barrels (approximately 61 – 90 million ton). To be able to increase the worker's safety and effectivity at Norwegian continental shelf, there is a focus on the use of drones and robotic technologies.

Figure 1: Johan Castberg oilfield on map [1]

2.2 FPSO vessels

The main principle of the oil and gas extraction from the oilfield is based on use of a FPSO vessel ("Floating, Production, Storage and Offloading") in cooperation with subsea solutions. These types of vessels, typically based on converted oil tankers, are equipped with hydrocarbon processing units that process and separate the extracted crude oil into refined oil, gas, and water. The extracted and processed oil then being stored on board in cargo tanks and later being transferred to land via “shuttle” tankers. Gas can be transited further to land via pipelines or used for on-board power generation.

The FPSO vessel is meant to be moored and connected to the subsea production systems by flexible flowlines. The overall overview of the standard FPSO solution can be seen on the Figure 2.

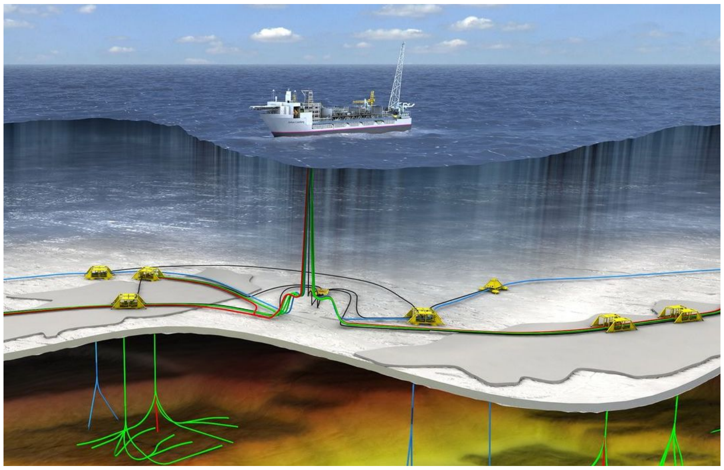

Figure 2: FPSO vessel and subsea system [1]

Johan Castberg vessel (Figure 3) is meant to be the “digital flagship" of the Equinor’s fleet and will be used as a base for testing of innovative technologies, including unmanned aerial vehicles. It has following basic characteristics:

- Total length – 300 m
- Width – 50 m
- Height above the waterline – 30 m

2.3 Barents Sea – Weather and Key Phenomena

2.3.1 Wind, air temperature and waves

Our area of interest is the southwest zone of the Barents Sea. This zone has specific climate conditions since it is affected by warm southern flows from the Atlantic Sea and cold streams of Arctic air masses from the north. Such combination can lead to high variability of weather conditions.

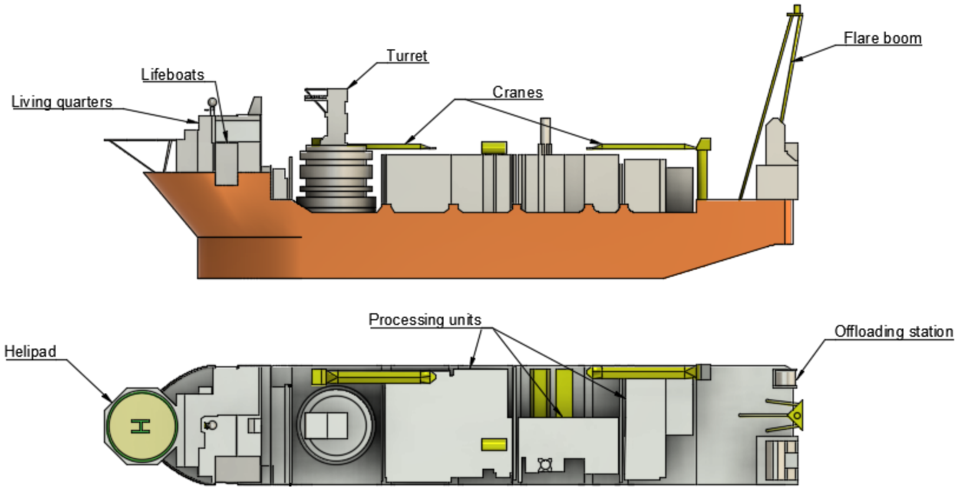

Figure 3: Johan Castberg FPSO

According to the statistics from the Russian center for World Ocean monitoring (ESIMO), this region is strongly influenced by cyclonic circulations and warm Norwegian coastal current [41]. This follows to small daily and interannual variability of the air temperature, stable wind direction but at the same time we should expect frequent precipitation and considerable cloudiness.

A mean wind speed is relatively slow - usually up to 10 m/s [42]. During winter wind speed increases severely, so we can expect maximum speed up to 30 m/s (maximum 1-hour mean).

Since the southwest region is affected by the cyclones and warm ocean streams, the air temperature is quite high (relatively to the high North regions), usually around -4 °C during winter and +9 °C at summer.

The mean height of waves varying at approximately 2.5 m. During winter, the maximum significant height can come up to 15 m or 7 m during the summer.

2.3.2 Key Phenomena

When the clouds are more relevant for the high-altitude operations, we can suffer from advection fog [43]. This type of fog occurs when warm air masses pass over colder water surfaces. The depth of the advection fog depends on moisture content in air, wind and temperature difference between air and water. Since it can last for a longer period under specific conditions, it can have strong impact on the performance of optic sensors on the drone.

Other phenomena that we can meet in the Barents Sea is so-called Polar Low, it also known as arctic hurricane, polar mesoscale vortex, or cold air depression. Unlike the advection fog, these hurricanes occur during wintertime, when cold air masses pass over warm water surface. A strong up-warded airflow is created, which lead to reduced pressure in local areas. This effect becomes worse when the upper atmosphere is also cold. Due to its small scale (diameter does not exceed 1000 km, usually 200-600 km) and short lifetime (up to few days), they are difficult to forecasting. For the drone operations they pose a danger in form of rapidly increasing wind (minimum 15 m/s with gusts up to 55 m/s), snow and/or hail showers, large wave growth and visibility reduction to less than 100 m [44].

Another weather phenomena that we can meet during offshore operations is the icing. It comes in several types: Atmospheric icing and ice accretion by sea spray [45]. Beside of vessels instability, icing can cause other risks, such as

- slippery decks and helicopter landing pad
- degradation or loss of communication due to ice on antennas
- stronger lateral wind due to increased size of structure components
- reduced visibility
- construction elements being blocked from inspection/sensors due to ice build-up
- falling ice

Atmospheric icing that can occur during offshore work can be divided into two subgroups: wet snow icing and freezing rain. For their accretion following conditions must present: Wet snow icing occurs snow falling at temperatures between 0 - 3 °C for wet snow icing and r water or drizzle drops onto surfaces with temperature below 0 °C for freezing rain.

Sea spray icing is similar to the freezing rain, but it depends on wind speed, temperature of water and air, wave height. It can occur on vessels and structures under the following conditions:

- high wind speed – usually above 9 m/s, sometimes lower
- low air temperature – under -1.7 °C
- low water temperature – under 7 °C

Since the oil extraction is performed in the High North regions, we should expect decreasing of optic sensor's performance due to polar night. Use of artificial lighting during that period can also affect the quality of sensing results. But when polar night plays negative role for optical instruments (since daylight and solar radiation affect the emissivity of the different materials that can give false positive results [19]) use of thermal imagery is more reliable [46].

2.4 Regulations and Requirements

2.4.1 General Directives and Regulations related to use of UAV

According to research results of members of ROBINS project, there are no direct regulations for remote inspection techniques of the marine inspections. There were not found any such regulations among Norwegian laws and directives neither, nor regulations related to autonomous UAS (Unmanned Aircraft System). The only mentioning of use of UAV for the ship's inspections were found in Requirements Concerning Survey and Certification, produced by IACS (International Association of Classification Societies) [47]. But it is only in means of additional inspection tool for visual inspection of hard-to-reach areas. There are only general rules related to use of the UAV/drones. Since there exist such a regulatory gap, we will base this research on existing regulations, allowing some assumptions in derivation of statements and decisions.

From the 01.01.2021 new regulations for UAS pilot certification in Norway are applied [48]. Drone operators that were licensed according to the older regulations (RPAS or so called "RO x" categories) before 01.01.2021 can continue UAS operations until 31.12.2021. New operators will need to proceed the processes of licensing according to new regulations.

In this work, older classification will be used, because it is still applicable and new rules related to specific use purposes are still not fully defined (as "Certified" category[1]). Also, new regulations are manly related to hobby/recreation drones (so-called "Open category) which has strong restriction of "weight/distance from people" relation (see Table 1 [49] and Table 2 [50]). Also, remotely piloted aircraft system (RPAS) categories are also still used in Equinor' documentation related to use of drones.

Use of drones is regulated by Norwegian Civil Aviation Act (Luftfartsloven): "Regulation on aircraft without pilot onboard[2] [51]. These regula-

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[1] per 05.02.2021

[2] Norwegian: "Forskrift om luftfartøy som ikke har fører om bord mv."

Table 1: Short overview of the Open category

Cat.	Name	Description
A1	"Over people"	- Can fly C0 and C1 class of drones - C1-UAVs and drones with maximum takeoff mass (MTOM) >250g can not be flown over other people
A2	"Close to people"	- C2 class drones - C2 drones must maintain 30m horizontal distance from other people - non-CE drones with weight max 2kg must maintain 50m distance - "1:1" rule applied: drones must maintain same horizontal distance from people as the height above ground level (AGL) is - Pilot have to pass theoretical exam
A3	"Away from people"	- C2, C3, C4 drones - >150m distance from residential, commercial, industrial or recreational areas - There should be no people other than those involved in the drone flying - If other person present: follow 1:1 rule with min 30m distance

tions are applied also for model UAVs and drones that are flying in airspace over Norwegian continental shelf and Norwegian economic zone. There are exists three drone operator categories: RO 1, RO 2, RO 3. They define requirements for organizations and sets limits for the UAV that can be operated. According to this regulation a company, which will operate drones, must have a team that consist of:

- Responsibility manager – responsible for the UAS division itself
- Operation manager – responsible for that all flight operations happens according to existing regulations and laws
- Technical manager – manage that all drones are in required technical condition

Table 2: Cx-marking of drones

Cx-class	MTOM [kg]
C0	<0.25
C1	<0.9
C2	<4
C3 and C4	<25

- RO 1 - aircraft with MTOM <2.5 kg, max speed 60 knots (30 m/s or 111 km/h), being operated within VLOS and safety distances defined by § 51[3]
- RO 2 - aircraft with MTOM <25 kg and max speed 80 knots (41 m/s or 148 km/h). Operates within VLOS or EVLOS and within safety distances defined by § 51 or BLOS in accordance with § 56 – § 59
- RO 3 - aircraft with MTOM $\geq$25 kg or max speed $\geq$80 knots or operates BLOS w/ altitude over 120 m or operates in controlled airspace w/altitude over 120 m or operates near crowd greater than it is described in § 51

While the minimum criteria is RO 1 certificate the RO 2 category is required, to be able operate offshore, including vessels and transit.

Beside of the official certification, the drone operator (pilot) must be approved by Flight Safety department in Equinor, which monitors all flight activities, including UAS, within the company.

2.4.2 Technical requirements

According to the existing regulations, drones (such as plans and helicopters) must be constructed also with respect to existing aviation standards. In addition to [51] and OM105.19 [52], there is also an EASA SERA rules [53]. According to them all drones have to be equipped with predefined set of sensors and lights. Most of these setups are used to achieve the safe piloting at nighttime. This becomes more important when operating in high North regions, when we need to deal with long lasting polar nights. By "night" EASA means the period between the end of evening civil twilight and beginning of the morning civil twilight [54], see Figure 4.

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[3] These paragraphs can be found in Appendix A

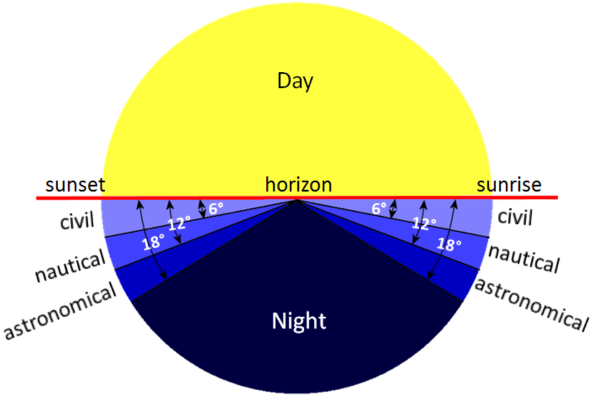

Figure 4: Visualization of different twilight [2]

To be able to fly beyond line of sight (BLOS), drone must have a white strobe light with minimal intensity 10 candelas and perform minimum 20 flashes per minute. For night flights navigation (direction) lights should be installed. They are used to indicate the relative path of the drone to an observer/operator. Most common way is to use green and red lights mounted on the right and left axle arms, respectively. Considering that there is still a requirement to have an external observer/assistant under flying, all flights is performed by manual control during daytime now. That means that there are no actual BLOS or EVLOS (extended visual line of sight) flights. Yet we are aiming for the automation of the inspection process, so these assistant roles will be replaced by other solutions, as for example by video surveillance. The proper illumination set up on the drone is necessary due to active helicopter traffic in the area.

To be able to use non-certified drones inside of the ATEX[4] classified zones, they must carry relevant gas sensor. It will not only be used to fit up the requirements but will also be part of inspection equipment for sensing possible gas or chemical leaks. Another sensor that we need to have onboard is an altimeter. Its role is to prevent violation of the altitude restrictions. Finally, each drone must have unique ID mark/token and be marked with operator's name and contact phone number.

In case of the remote-control failure, all drones must have an automated landing system. In our case, drones should have a backup radio connection that ensures telemetry and telecommand transmission to ensure that drone

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[4] ATEX – ATmospheres EXplosibles, potentially explosive atmospheres

always has updated its own and vessel's position. Most of these requirements will be naturally fulfilled because they are critical for the successful execution of the mission.

One additional requirement to remember is that neither drones or any one component of the system should provide any risks for the crew and for technical equipment/components of the vessel and surroundings. There should be performed thorough assessment for choosing of different components (such as materials, motors, batteries, etc.) that will be used.

2.4.3 Operating in ATmospheres EXplosibles

An FPSO vessel has high explosion danger. To be able to perform any inspection or maintenance tasks, drones and all supply infrastructure should be designed, manufactured, implemented, and run according to specific regulations and directives.

The basic directive for equipment (i.e. drones and its supply infrastructure) and protective systems are ATEX Directive 2014/34/EU (also known as ATEX114) which has replaced an older Directive 94/9/EC [55]. Beside of the concentration of the flammable/explosive gas, vapor or mists, the new directive also include concentration of potentially dangerous dust, and probability of the ignition from mechanical and electric systems.

There is also the directive for improving the safety and health protection of workers: Directive 1999/92/EC [56]. In Norway, the regulation equivalent called "Regulation for equipment and safety systems to be used in hazardous areas[5]" [57] is used.

To get an ignition of flammable materials or gasses, three conditions have to meet: fuel source, oxidant, and ignition source. Fuel source is simply combustible dusts/gas or flammable materials. In case of oil tanker or an FPSO, we cannot cut it out, so other solutions are needed. One of the ways to prevent ignition is to remove the oxidant, where oxygen is the most common substance. To achieve that, inert gasses can be filled into the tanks to reduce amount of oxygen. Finally – ignition source. UAVs and their supporting infrastructure usually contain electrical and mechanical components, that can represent ignition sources. It can be in form of heating, electric sparks, or electrostatic discharge.

There are defined so-called ATEX-zones, that are derived from the United States' HAZLOC (hazardous locations) standards [58], based on the gas/vapor

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[5] in Norwegian: "Forskrift om utstyr og sikkerhetssystem til bruk i eksplosjonsfarlig område"

or dust concentration in the air that may cause an so-called "explosive atmosphere", see Table 3. It is important to mention that variation of h/year is not officially defined, but rather an attempt to place time limits into zones [59]. Areas that has not been divided into one of the mentioned classes, are classified as safe or non-hazardous. The simple visual example of such classification on schemed gas station can be seen in Figure 5.

Table 3: Classification of the ATEX zones

Probability of the gas or dust are present	Zone code for combustible gas, vapor and mist	Zone code for combustible dust
Present permanently or for long period (>1000 h/year)	Zone 0	Zone 20
Present during normal operations >10 h/year and <1000 h/year	Zone 1	Zone 21
May occur <10 h/year	Zone 2	Zone 22

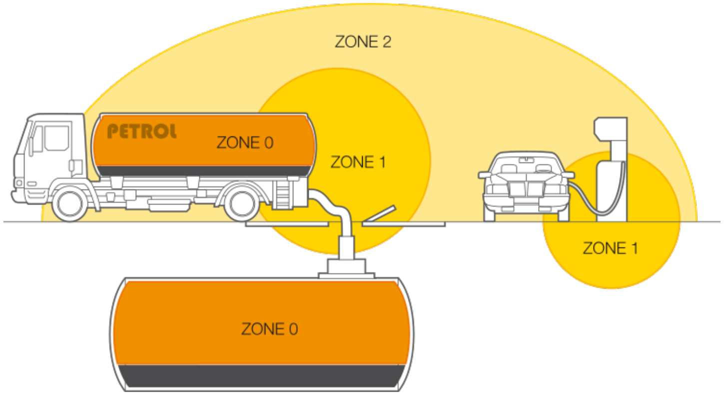

Figure 5: Visual example for ATEX zone classification [3]

In our situation drones and their supply systems will operate under conditions when explosive atmospheres are presented during normal operations or may occur (depends on place on the vessel, see Figure 6). So, they should be classified as Equipment group 2 – category 2 and 3 respectively [57]. Gear that will be installed in Safe zones does not fall into any of the ATEX classification paragraphs, but still should be certified according to internal standards. Based on this classifications and national laws, we get following

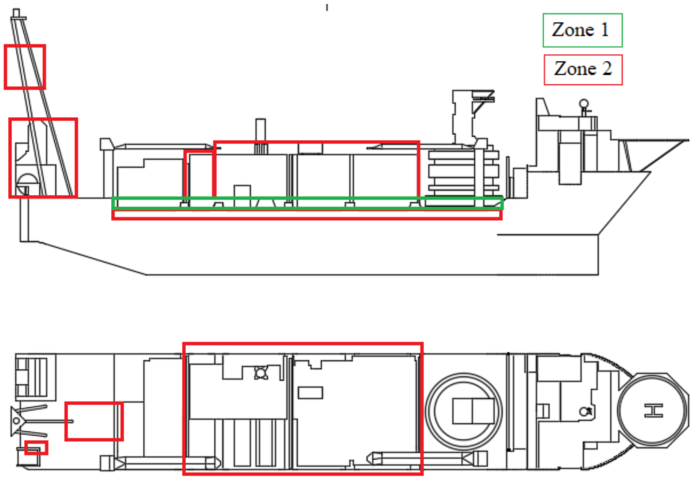

Figure 6: ATEX zone on Johan Castberg

requirements for the equipment[6] that will be operating/installed in hazardous zones:

- General Requirements:
  - The equipment shall not pose danger by itself or emit explosive atmosphere.
  - The equipment shall not pose possibility for ignition of the explosive atmosphere by its electric and non-electric components.
  - Risk assessment shall be performed prior to equipment's construction, production or operation
  - Possible human factor should be included into risk assessment.
  - Materials that are used in equipment should not go into reaction with environment and constituents of the explosive atmosphere.
  - Components should not pose any potential ignition source as sparks, flames, electric arcs, high surface temperature, optical radiation, electromagnetic waves, electrostatic discharge and others.
  - Components of the equipment should be capable to perform under expected stress and resist strain from aggressive substances that are present or may occur.

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[6] here: all physical parts and components of the inspection system, such drones and installed external equipment (e.g. sensors and aerial manipulators), UAV landing pads, navigational radio beacons, etc.

  - If failure occur, there should be possibility for equipment to switch into safe mode.
  - Equipment that is operating in autonomous mode, should be able to be stopped manually in a safe way if operating conditions change beyond its assumed limits.

- Extra requirements for equipment of group 2 category 1:
  - In case of failure of a protective system, there always should be at least one reserve system, such that required level of safety remains.
  - In case of two independent failures occurring simultaneously the required level of safety should be remained.
  - If the equipment's surface can become hot, it should be ensured that the expected maximal temperature is not exceeded, even in unexpected environmental conditions.
  - It should be ensured that the surface temperature is considerably lower than ignition temperature of the explosive atmospheres.

- Extra requirements for equipment of group 2 category 2:
  - Equipment should be designed and manufactured in a such way that it does not present an source of ignition (also in case of possible damage or failure).
  - Equipment and its parts should not be heated over desired limits, also in abnormal situations that were anticipated by manufacturer.

- Extra requirements for equipment of group 2 category 3:
  - Equipment should be designed and manufactured in a way way that it does not present any source of ignition.
  - The temperature of the surface should not exceed desired limits during normal operations. In special cases these limits can be exceeded only if the manufacturer includes additional protective solutions.

Per 15.02.2021 there does not exist any ATEX approved drones. Only two quadrotors that could be operated there:

- "Parrot Bebop 2 light cage drone for inspection in Hazardous areas" - prototype, light weighted (0.5 kg or 1.1 lbs) that can be used for indoor inspections, ATEX Zone 1 or 2 rated (*certification pending*) [60]

- "Explosion Proof Drone" - features maximum distance of 3.2 miles (4 km) and 22 minutes of flight time, MTOM 15 kg (33.3 lbs) so it can be used for outer inspection. ATEX Zone 1 rated (*certification pending*) [61]

3 Use Case Scenarios

The main tasks for the implemented UAV systems are to perform different types of inspection and maintenance on FPSO vessel.

This type of vessels is a large and mechanically complicated structure. Being a part of the country's energy policy, they play a significant role in the national economy and wealth. By introducing and combining the old classic systems with modern technologies, we want to achieve few goals: increase the effectivity of oil/gas production and increase the employee's safety.

By "inspection" we mean the mission when a drone or an array of drones performs an inspection of the vessel's hull, on-board components/structures in a way that gives the same or better results that are usually obtained by a surveyor. All inspections should be done with respect to the maritime organization's standards [62], company's internal regulations and manufacture's recommendation.

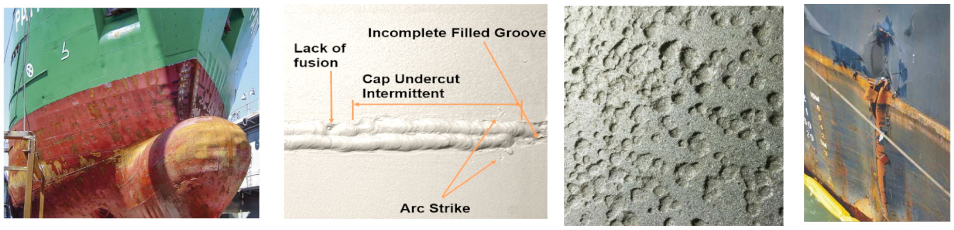
In the ROBINS project, the objective of ship inspection is defined in the following way [22]:

> *"The objective of ship inspection is to verify the structural strength and integrity of essential parts of the ship's hull and its appendages, and/or the reliability and function of the propulsion and steering systems, power generation and those other features and auxiliary systems that been built into the ship"*

To be able to rationalize the inspection and maintenance intervals, as same as set up relevant scenarios, it is important to identify and understand various failure and degradation mechanisms that can occur during the vessel's operational time. Rightly identified processes will help to reduce dry docking time, reduce risk factors, avoid economic and environmental consequences.

Any failure newer happens "by itself". Usually, it is the chain of some natural processes that unfortunately can cause failures and losses. Specifically, for the FPSO vessels, following degradation mechanisms are considered [63] (Figure 7)

- Corrosion
- Welding defects
- Wear
- Erosion



(a) (b) (c) (d)

Figure 7: Most common degradation mechanisms: (a) wear in paint (b) welding defects (c) pitting corrosion (d) buckling

- Cracks
- Buckling
- Holes

These mechanisms can act alone or combined, vary in intensity, and can lead to fatal structural damages. Failure mechanisms that can occur as resulting impact of degradation mechanisms are described as loss of functionality of a structure(s) or system(s). The most usual cause of failure mechanisms occurrence is missing or inappropriate inspection routines. The most important consequences we can get are:

- Compartment flooding
- Buoyancy loss
- Fire or explosion
- Leakage
- Structural integrity loss

Based on that information we can derive four main use-case scenarios:

1. **Mechanical/structure inspection** – by using different type of scanners/sensors, nondestructive testing method and image processing, perform the control of the vessel's outer and inner structure (such as hull, on-deck machines and mechanisms, oil/gas/ballast tanks)

2. **Environmental inspection** – by using different type of sensors, detect and prevent oil spills, gas leakage and overheating/fire;
3. **Safety** – prevent hazardous situations on-board. In case of any critical situation, we can get an "overview" image of the scene fast and keep track of the crew members. If someone falls overboard, we can spend less time locating the person and by using the additional equipment on the drones it will take less time to get him or her back to safety.
4. **Maintenance** – using aerial manipulators, gripper arms and other tools we can perform simple repair tasks and transport light-weighted items within the vessel.

These groups are also divided into subgroups, as will be seen later. Some of them can be related to different main groups, in this case they will be referred according to their "primary" abilities.

3.1 Use-case 1: Structure and mechanics inspection

This is the main scenario for our inspection system. Its goal is to inspect the vessel's hull, superstructures, processing units, oil/gas, and ballast tanks for possible wearnesses and deformations.

The main components of the hull structure are side shell plates and reinforcements which are connected by welding joints (see Figure 8). Due to interconnection of these individual components, integrity loss of single elements can lead to hull/structure failure, ensuing economic or environmental consequences. Since we want to perform inspection of the outer and inner components of the vessel, we can split this scenario into two subdivisions: External and Interior inspections. They have the same goal and are part of one system, but they require different approaches.

Scenario 1.1: Exterior Inspection

During exterior inspection we are using the set of sensing equipment installed on the UAVs to control the outer hull, machines and construction elements that are placed on the deck. This includes detection of corrosion, deformations, heat exchange, icing and others. All these procedures will be done under challenging environmental conditions which put high requirements on design of UAV and choice of sensors.

Based on these factors, we can derive the following key scenario elements (impacts):

- Open space – as sensing being performed in open sea

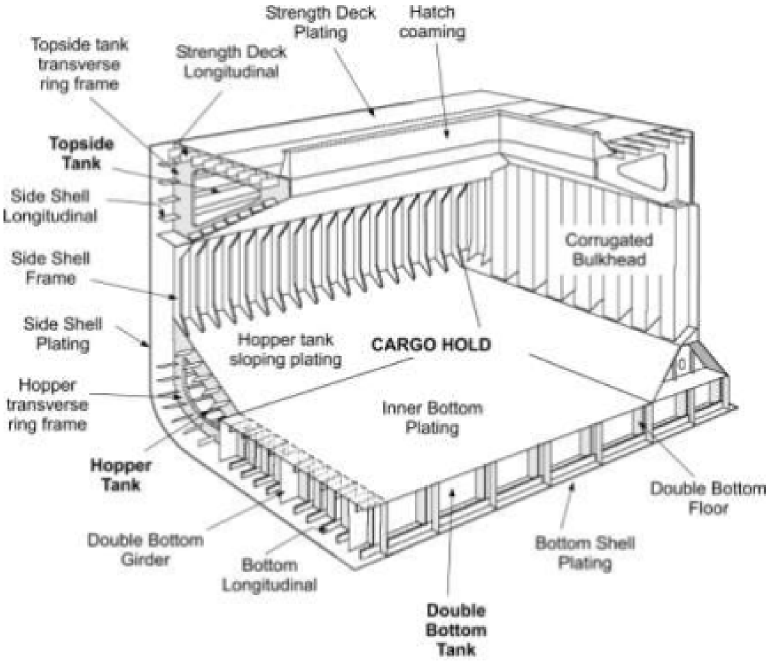


Figure 8: Hull Structure [4]

- Aggressive environment – low temperatures, strong wind, saltwater splashes, icing (on drone)
- Complex path/sensing planning – requires high number of waypoints with specific camera/sensor tilt angle, distance from the objects, hovering during some period is required
- Movable platform – vessels can experience the motion in 6 degrees of freedom: rotational (around yaw, pitch, roll axis) and translational motion (heave, sway, surge), also when anchored.
- Hazardous explosive atmospheres
- Prolonged loss of light at wintertime

In addition to a harsh environment, drones can by affected by high-temperature surfaces of the processing structures, which can have temperature up to 400°C [35].

For the outer inspections, drones will form a high-level technological base that is capable to provide enough stability and reliability to succeed the inspection tasks.

According to requirements described in [64][47][63], we get the following overview (Table 4) of the critical structure areas and the deformations that are expected to be representative there. This table does not contain information about *all* possible degradation factors and structures on the vessel, but that are most relevant and feasible to be detected under an UAV inspection.

Table 4: Exterior inspection: structure components and expected weaknesses

Structure elements	Expected deformations/weaknesses
Hull	Wear, erosion, corrosion, cracks, heat exchange, welding defects, buckling, holes
Processing equipment	Icing, heat exchange, gas/liquid/oils leaks
Turret/transfer system	Corrosion, icing, heat exchange, gas/liquid/oil leaks
Flare boom	Icing, rust, buckling, cracks
Deck cranes	Icing, rust, buckling cracks

Scenario 1.2: Interior Inspection
The main goal for the interior inspection is the continuously updated condition status of the oil and gas tanks. These high-volume storage tanks present a wide area with significant heights (up to 30 m). While drones will not suffer from severe sea weather and a strong wind, it will face the demand for precise automated navigation and orientation techniques. Being surrounded by thick metal constructions, GPS-based navigation system is not available. The use of optical sensors can be challenging because of poor or non-light, same as implementation of laser-based solutions can be difficult as any uniquely shape that can be matched across the scans are not present.

Beside of oil storage tanks, vessel is equipped with ballast tanks that are also interest for inspection. These tanks carry water to provide stability for the vessel. Their inspection is relevant for overall structure integrity, because of highly corrosive effect of salted seawater. At the same time, empty tanks are also affected by damped air which also increase corrosion impact on the tank surface. Unlike wide area oil tanks, ballast tanks are usually presented as cluttered environments with a lot of obstacles.

Briefly, we can set up the following key features of the inner inspection scenario like:

- Enclosed space

- Complex navigation conditions
- Man-hole sized[7], single entry points (hatches)
- Hazardous environment
- Impossible use of magnetometer-based sensors
- Cluttered environment of ballast tanks

During inspection of storage tanks, our main interest is to follow the condition of tank's coating since it is their main protection solution. It is also of interest to check the welding joints, as same as level of vibration of the shell plates placed near machine/engine rooms. General defects that can occur inside the tanks are similar to that what affects the hull: corrosion (most common), deformation and fracture.

Due to clattered environments, especially in ballast tanks, it is desired to have a collision-tolerant drone. Possible solution is to use multirotors equipped with specific protective cage, as for example been mounted on Flyability Elios drone [66](Figure 9).

It is also important to remember that an ATEX certified drone is needed for inspection of tanks containing hydrocarbons. While there are no such drones developed, tanks need to be prepared for inspection. In other words, they need to be empty and approved as "safe" prior to each inspection. It also necessary to empty ballast tanks if we want them to be inspected by UAV. Instead of UAVs we could use autonomous underwater vehicles (AUVs), so they can perform inspection without draining water. But in this case, resulting visual-based inspection quality will be reduced due to filthy waters. Use of unmanned ground vehicles (UGV) does not seem possible due to their obstacle-overcoming limitations in cluttered and confined environment.

3.2 Use-case 2: Environment monitoring

While inspection of structures and equipment under normal operations is related to standard external inspection scenario, here we are interested to detect any environmental accident (in other words leakage). It can be in form of oil spills, gas or other chemical substance leakages. The goal of this scenario is to get a warning at the moment leakage has been detected. This scenario is meant to be performed during daily normal operations, so we do not expect any specific impacts (as for example high temperatures from the

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[7] Most common: from 300x300 mm to 1200x1200 mm for square/rectangular and ⌀450-600 mm for circular covers [65]

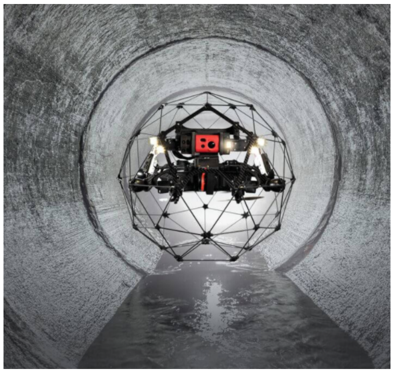


Figure 9: Collision tolerant Flyability Elios drone [5]

flames). Hence, the scenario key features are the same as for Scenario 1.1 "External Inspection", except possibility that the drone can get impact from the chemical suspension in case of leakage.

To detect oil spills we can use already installed video and infrared cameras. Some studies show satisfying result on using IR images and computer vision for its detection [67][68]. Tests shows that use of short-wave infrared (SWIR) band (1000–1700 nm) is highly effective to detect spills in low light environments [69]. During operations following gases can be present:

- volatile hydrocarbons emitted from crude oil during different processing stages
- vaporized hydrocarbons, as for example:
  - natural gas (consist of methane, ethane, propane, butane)
  - gas compounds, as for example benzene

Crude oil usually have a certain amount of natural gas where methane is the primary component (87 - 96%) [70][71]. So, instead of several different sensors for each specific gas, we can have only one for methane detection. There are some types of sensors that are suitable for its detection, with the most common non-dispersive IR and laser-based sensors [72]. The main difference between them is that IR camera works as "area" detector, so we detect leakages on an entire image (camera's field of view), while laser is suitable for spot detection on selected object (gas pipe, valves, etc). In our case, sensing all possible pipes, valves or fittings will take a lot of time, and most of these pipes will be unreachable for laser beam or camera due to coverage by other pipes or mechanisms. Using a camera with a wide field of view is thus more reliable than single spot sensing.

3.3 Use-case 3: Safety

Scenario 3.1: Scene monitoring

While the first two scenarios are pre-planned and performed during normal daily operations, this scenario starts in the case of emergency situations. The main idea is to assist an emergency response team (ERT) with scene monitoring. The core meaning is to deploy all suitable drones and get image of the scene within minutes after an alarm goes off. Using thermal cameras, we can detect fire hotspots, monitor the fire's spread (also inside of the vessel) and be able to track crew members through the smoke.

The scenario key features are the same as for Exterior inspection, with several additions:

- more aggressive environment – due to high temperatures in case of fire or explosion
- extended airtime
- possible degradation of navigation capabilities – due to partial or total loss of local navigation equipment on board the vessel
- possible degradation or loss of power supply infrastructure (charging possibilities)

To prevent loss of communication, additional GNSS receivers can be installed on UAV. Also, reserve channels for telecommand data transmission from the vessel is recommended. This is to have an effective control and safely land the drones also in critical situations. It should contain data of vessel's inertial navigation system, that allows to steer the orientation of the drone relative to the ship.

This specific scenario can be challenging to perform in fully autonomous mode. Most likely it will be performed in semi-autonomous mode when operator manually defines positions and orientation of drones by request from ERT captain.

Scenario 3.2: "Man overboard"

In this scenario we are aiming on safety of the crew members who accidentally falls overboard. So, the goal is to use drones to locate the person in water and transmit this information to the rescue team. In this situation each seconds counts due to exposure to low water temperatures, which can cause hypothermia. At the same time, especially during stormy weather, person can be drifted away by wind and ocean current. This situation can be deteriorated by night time.

Unlike the inspection or maintenance scenarios which are predefined, we cannot predict this kind of situation. To be able to adequately react to changed inputs, we might implement the priority of the scenarios (events), in a such way that "Safety always comes first", see Table 5.

Table 5: Task priorities

High	- emergency situation, risk for crew
	- emergency situation, no risk for crew
	- environment-related incidents (spills and leakages), no potential risk for crew
Low	- ordinary inspection

The scenario key features are also the same as for exterior inspection one. This scenario can have two variants:

1. when we *already know* that someone is missing;
2. when we *do not know* it yet

These variants involves different approaches. In the first situation we need to localize the person, which requires active search. In this case we can use infrared imaging with image processing to be able to find the person. Combination of thermal imaging and computer processing is a widely used solution for maritime search and rescue operations. There are proposed effective solutions for implementation of such IR sensing in [73][74]. For successful execution of the second variant, additional technologies must be implemented. To get notification immediately after falling, we can use radio distress beacons integrated in uniform or into life jackets (which are preferred). When the beacon comes in contact with water it starts to transmit the distress signal, so rescue operation can start immediately. To be able to save a time locating a person, additional GPS antenna that will transmit a coordinates can be also integrated into the life vest. Such solution is used in Cospas-Sarsat satellite system [75]. It shows impressive results in real-life conditions. A drawback of the satellite-based solution is that it takes some time the alert is activated. In our situation we have ability to reduce that dead time to few seconds by transmitting distress signal directly to local receiving equipment.

3.4 Use-case 4: Maintenance. Use of Aerial Manipulators

Scenario 4.1: Use of Aerial Manipulators

To expand inspection opportunities and be able to perform maintenance tasks, the aerial manipulators can be installed on the drones. This will provide the possibility to perform different sensing tasks in hard-to-reach areas. For this specific task, the series-connected multi-DOF arm attached to a drone's frame is preferred. It will allow free use of end effector without need for additional compensation of moving limitations by drone. That will give us possibility to use different end-effectors without changing the whole arm, nor use drones that are dedicated only to one specific task.

There exist several important limitations today,where the first one is high power consumption. It is related not only to amount of energy needed by end effector, bit also power required by drone to counteract the moving center of mass [76]. Adding additional batteries will not solve that problem, because power consumption will also increases with increasing total weight. So, there is demand on new types of light-weighted batteries with higher energy density. The second limitation is complex modeling and control [77]. The main idea is that drone positions as an anchor for the manipulator, in the same way as ground-fixed base, in term of reaction forces. To solve that problem, we could use drones that can "stick" to the walls using e.g., electromagnets. To overcome resulted increasing of power consumption we could use tethers, but it will reduce the drone's operational area.

Based on these drawbacks, we can see that there are not many possibilities to implement drone-based maintenance or repair system today. There is only few possible application ways how to use aerial manipulators: "extender arm" for sensors or grippers and to lift some light-weighted items.

Scenario 4.2: Maintenance assistant

Even though we are not able to use drones in repair tasks, they can serve to help the personnel during maintenance operations and with some small tasks. Drones can be used as external light source, tools holder and transportation of items within the vessel. Additionally, sensing drones can be used on-demand by maintenance team. For this scenario it is necessary that drones are equipped with additional sensors for obstacle recognition and highly accurate object tracking algorithms must be implemented, due to close flying/hovering to the personnel and structures. For extra safety, propeller guards can be installed. There should be possibility for the drone operator to quickly and in safe manner move the drone away from the person in case of any unpredicted situation.

It is also desired that this type of scenario will be performed in last stages of the automation, because operating in short distance from people can pose a danger.

Scenario 4.3: Anti-icing

Another possible way to use drones is to perform deicing or anti-icing of the vessel. Sea spray is the main reason for icing occurrence on platforms or vessels and is one of the major hazards in cold regions [78]. Unfortunately we will not be able to crush ice that already occurred on the vessel or structures, see Figure 10. Even today the most common way to remove ice from decks and structures is by using man power and shovels, wooden bats or hammers. Seas spray could be also avoided by heading or maneuvering downwind. Unfortunately, this solution is not applicable to FPSO vessels, because they are anchored and tend to head upwind to keep the flame at flare boom away from the ship. Because of that positioning, the most likely areas for ice accretion are bow side, helicopter pad, front sides superstructure, lifeboats, upper parts of turret and flair boom and cranes. Another techniques for deicing are use of chemicals agents and deck heating (electrothermal) elements [79]. Use of such agents can be also challenging due to its possible impact on environment and as they can cause metal corrosion vessel's structure. Beside that, use of drones to minimize the ice accretion by anti-icing operations (in other words spray chemical agents in prior to icing) seems feasible. There are already been used tethered drones to clean, de-ice and apply coating on wind turbines by Aerones Drone Solutions [80]

Figure 10: Sea spray icing on ships [6]

Similar solution for spraying is implemented by DJI on their agriculture drones, as for example MG-1 octocopter [81]. It is designed for agriculture needs, but main principle can be used for spraying anti-icing agents. According to its manual, it can carry up to 10 kg liquid, has spray width 4-6m and spray rate 0.43 L/min [82]. Unlike the Aerones' solutions, drone from DJI has onboard tank and batteries, so is not affected by tether limitations. It shows that implementation of "spraying" drone is feasible and can be used in this project.

The overall scenario key features are similar to those for Exterior inspection, but with several additions:

- flying and/or hovering close to constructions and personnel – need for additional and precise obstacle avoidance sensors and algorithms
- drones or supporting infrastructure can be damaged by falling ice – detection of the ice have to be a part of exterior inspection use-case

4 Concept

4.1 Choice of suitable drones

After relevant requirements and use-case scenarios were set up, we can choose relevant types of drones for the inspection system.

There are different approaches of UAV's classification [83]. This configuration variety is based on all spectrum of platforms and missions. Today, the most used way to differentiate the drones, is by their aerodynamics and maximum weight, which simplified version shown in Figure 11. There are many more types of drones, such as flapping wing, "smart dust" (insect-scale PAV), taxidermy bio-drones and others [83]. They are not included into that diagram, because most of them are designed for specific use (such as unmanned combat aerial vehicles), research platforms or other miscellaneous applications (as police interceptor drones). So, they are not applicable for maritime inspections. Other classification methods are based on different drone parameters, such as dedicated application, flight altitude, range, endurance and motor energy, as well as on their different combinations [84][85].

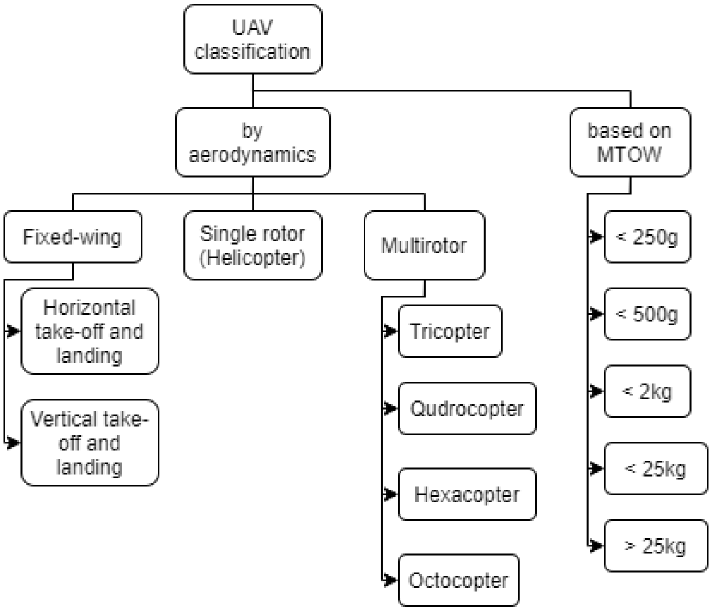
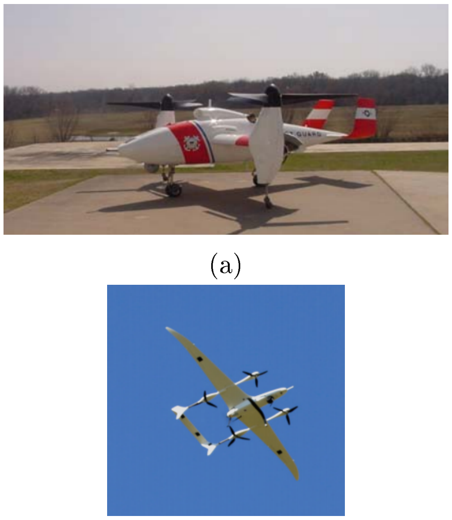


Figure 11: Classification of UAV based on aerodynamics and weight

The most widely used drones nowadays are fixed-wing and multicopters. Advantages of the fixed-wing UAVs is that they can fly for a prolonged period and cover wider areas than multirotors, since we do not need to constantly generate lift in addition to drag force. Another big advantage is their robustness in case of motor stalling - wings will still allow them to glide and perform a safe landing. A challenge is implementation of take-off and landing solutions. For the launching we will need a large and open area without obstacles. Use of hand-launching could be a possibility, but then we will bring another problem - to be comfortably operational by hands, drone have to be lightweight. However, use of lightweight drones means stronger restrictions for flying in windy conditions and additional weight limitation for payload. Possible solution could be use of the catapult launcher. It takes small place and reduces chance of human error, but it will not solve the landing problem. There are some approaches for landing the fixed-wing UAVs [86]. It could be the already mentioned runway, belly landing, net recovery, parachute recovery system or deep stall landing. There was also presented an applicable approach of net recovery for maritime use using suspension by two multirotor UAVs [87]. Unfortunately, all of these methods, except of runway, are not sufficient for our use, because under each landing drone and sensing equipment (payload) will suffer from a shock impacts, which will shorten their life span and will cause misalignment of sensors. Additionally, fixed-wing drones can not hover. So we can use them only for overall video inspection from a distance, without any possibility for specific spot inspection. In this project, they could be used when prolonged flight is needed, for example if we need to seek after a person in water or for operational monitoring of oil spills. There exist a hybrid version of a fixed-wing UAV - VTOL (vertical take-off and landing). It allows the fixed-wing drones (Figure 12-a) to take-off and land on a spot without need of a runway. They are designed in few ways: tiltrotors and additional vertical propulsion system (it has rotors that are dedicated to generate lift, see Figure 12-b)

The takeoff-landing problem could be solved by use of helicopters. Unlike the fixed-wing UAVs they can hover and at the same time have longer endurance than multirotors. Large rotor blades give higher payload capacity and greater flight range. Another positive side of helicopters is that they are easier to stabilize than quadrotors. Using variable-pitch blades gives the possibility to effectively counter-react external impacts and stabilize drone or change thrust much faster, as we do not need to add delay-time due to inertia of four or more motors. Additionally, it helps to save energy, especially while hovering. So, if we would like to transport heavy loads on long distances, the helicopter UAV is a perfect solution.

Unfortunately, one of their disadvantages comes from their advantage. To be able to steer pitch and roll angles, a mechanism called swashplate is used



(a)

(b)

Figure 12: (a)Tiltrotor [7] and (b)hybrid fixed-wing UAVs [8]

(Figure 13), which is complex both in construction and maintenance. While we need only simple electric stabilization units (electronic speed controllers) connected to each motor to steer the same angles of rotation on a multirotor. Since also we have only one main rotor, in case if motor stalls or blade damaging, we will not be able to safely land the drone without causing any other damages. Additionally, bigger blades can inflict harm on personnel, cause fire or damage different mechanisms. These are reasons why we do not want to use helicopters for the close-up inspections, while they could be used for freight transportation if needed.

Unlike helicopters, multirotors (3+ rotors) are usually equipped with fixed-pitch blades and uses controllers that control rotational speed on each motor. Changing speed separately on each motor gives us possibility to control the thrust and torque of motors, thus steer the multirotor. It gives cheaper operations and maintenance with increasing reliability, as we avoid use of complicate mechanisms. Using the blades of smaller diameter also reduces harm of possible damage, thus increases safety. Another advantage of using only electrical motors for flying, is that they are the only moving parts (except of camera's gimbal, but it is not dedicated for flight control) on the drone, as we do not have swashplates, ailerons and others - so the probability of failure is lower. On the other side we have reduced flight time and lower payload capabilities [88].

Figure 13: Helicopter swashplate setup

Multicopters can have various configurations, but the most common are 2-blade puller, quad-/hexa-/octocopter [88][89]. Even number of motors is preferred, because it gives balanced torque. Using odd number of motors (e.g. tricopter) will require a tilting mechanism on one of the motors in order to balance the torques [90]. Main advantages of using more motors, like comparison of octocopter to quadcopter, is increased payload capacity, higher speed and possibility to tolerate failure of several motors. Unlike quadrotors, hexa- and octocopters can still hover, fly and perform safe landing with up to two stalled motors, while quadrotor can become uncontrollable with a single motor failure if proper control laws are not implemented. There are proposed different approaches to make a controlled landing, such as PID-based approach [91], cascaded control method [92], nonlinear H_∞ control loop sharing technique [93] and T^3 mechanism [94]. Anyway, while some of these techniques shows sufficient results, we are not able to fully control the attitude of a quadrotor if one of the motors stalls because it can suffer from uncontrolled spins about its yaw axis [95]. It can cause unwanted damages, thus use of hexacopters is more preferable.

The choice of drone type and configuration is always based on mission definition and environmental effects. Besides, it is desirable to have similar types of drones to be able to reduce operational and maintenance costs. Since we will perform a marine inspection operation in complex weather conditions, the hexacopter configuration is recommended for the exterior inspections. Use of fixed-wing drones would be preferred for emergency scenarios, when prolonged flight is needed, but it will require installation, or having available for fast deployment, of additional supply infrastructure.

Due to limitations on performing automated inspections of cargo holds and ballast tanks, we will not be able to implement automatic fly-in into them. Also due to clattered environment of ballast tanks we will not be able to use big and complex inspection drones that will be used for outer hull inspections. Therefore there are few ways for drone assignments:

- We will have drones for outer inspections only in addition to drones, dedicated for inner inspections (cargo holds *and* ballast tanks).
- Or we can use the outer drones also for inspection of cargo holds (so long they can fly through manhole size hatches) and have drones dedicated for ballast tanks inspection only.

It is important to keep in mind, that inspection of ballast tanks is only possible when they are emptied. To be able to inspect these tanks while there is water inside, additional unmanned underwater vehicles (UUV) could be integrated into inspection system. This will allow us to unify UAVs and save time by skipping emptying process.

4.2 Inspection techniques

As it was set up in use-case scenarios, there will be performed few types of sensing: visual and contact. Both techniques are being parts of an non-destructive testing (NDT) methods, widely used in civil engineering structures, as they allow to validate the properties, detect internal and surface defects of steel materials or welds without damaging them. While most of these damages can be detected by simple visual approaches, the use of contact methods can give more precise results.

Unfortunately, due to limitations of the UAV platform (such as payload capacity, limited power supply, short flight time) we cannot use the wide specter of NDT methods.

The most common techniques that are used to detect cracks, weld defects, corrosion and measure thickness of metals are [96][97] visual and ultrasonic.

Visual:

Inexpensive, and common type of NDT. Usually, it does not require additional equipment and can be done just by naked eye. In our case we will use it with remote visual inspection (RVI) tools (e.g. camera) installed on a drone. With all its simplicity, this method has its drawbacks and disadvantages. Only visible defects can be found, and requires good and correct lighting. On the other side, image processing techniques will give us an opportunity to detect cracks and deformations on their initial stages, such that we can prevent damages and failures. Also, mapping of discovered weaknesses and degradation prior to annual inspection will allow optimization of the repairing process which will reduce dry-docking time, thus costs. According to the set up of use-case scenarios, we will need a few types of cameras: ordinary video, infrared SWIR (short-wave infrared) for oil spill and ND-IR (nondispersive infrared) gas leak detection.

Corrosion detection is one of the important parts of the ship's inspection process [47]. There are several types of corrosion, but most dangerous is pitting since it is hard to predict and detect [98]. For its detection, several methods can be used, as for example magnetic flux leakage and ultrasonic testing [99], but most of these tests are expensive, have limitations to access introspected areas and heavy. Also, in our case we have big areas of metal plating (shell plating of hull and cargo tanks), so contact-based inspection will not be effective due to high time consumption. So, to be able to quickly gather information we can use image processing techniques to detect potentially rusted areas. Then, as a second step, use ultrasonic testing to collect sensor probe data of suspicious points. Use of neural networks for automatic detection of corrosion spots and cracks shows satisfactory results. For example, LSHADE-SVC-PCD model (image processing based detection of corrosion) [98] gives a classification accuracy rate (CAR) of 91.80%. Or image texture analysis by MO-SVM-PCD model, which has achieved CAR of 91.17% [99].

Because of dependence on proper light conditions, CAR can be lower with a probability of false-positives, or small spots can be left undetected. Still, as an alternative to time consuming contact-based detection systems, visual-based image processing approach is promising.

Ultrasonic:

This method is based on use of high frequency sound waves and uses to measure thickness of metal plating. The most common variant is pulse-echo detection. Here the sound waves are sent into the material and reflected echo produced by defects is then being detected by sensor. By this type of testing, we can detect hidden cracks, welding defects (most common is incomplete fusion) on target spots. One of the advantages of that method is that we require access to only one side of metal component to be able to measure thickness. This test can also help to confirm or deny the suspicious corrosion spots discovered by image processing. According to [47], thickness being measured during each Special and Intermediate inspection.

Other methods, such as powerful ultrasonic guided waves approach, which is widely used for corrosion and crack detection in pipes, could allow to inspect the whole area of cargo holds/ballast tanks plating [100]. It requires installation of additional transducers, so it cannot be installed on and operated by a UAV.

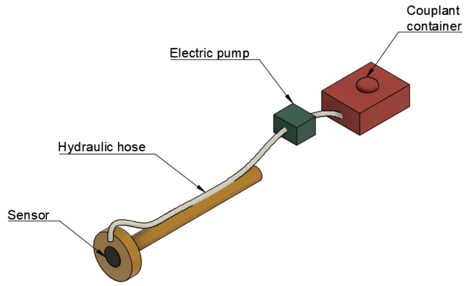


Figure 14: Simplified design of couplant supply system

One of the disadvantages we can face up with when using this type of sensing on a drone is that it can give false positive echoes if the sensor is not aligned properly to the inspected surface. We also need to keep in mind that air is not an effective conductor of sound waves in megahertz range. So additional couplant between sensor tip and test surface, such as propylene glycol or gel, is required [101]. To be able to provide couplant on sensor surface, an additional mechanism should be installed on the drone, example can be seen Figure 14.

So far, the most feasible and cheapest NDT solution, that can be installed on an airborne unit, is visual-based image processing inspections. It is because their sensors have small coverage area or requires installation of additional equipment (as transducers or mercury lamps) on vessel. There are also needs for long lasting flight time and more aggressive control to be able to keep the drone in one position relative to the vessel. So, the main possibility to use contact-based inspection techniques is to use them to inspect doubtful spots, detected by image processing, or for pre-planned check of critical structural areas [96].[8]

4.3 Frames of reference (coordinates)

To define the attitude of inspection drones and create mathematical model for simulations and path calculations, it is important to set up the reference frames. It will also help to visualize data flow and specify which components of supply infrastructure are needed.

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[8] Critical Structural Areas are locations which have been identified from calculations to require monitoring or from the service history of the subject ship or from similar ships or sister ships, if applicable, to be sensitive to cracking, buckling or corrosion which would impair the structural integrity of the ship.

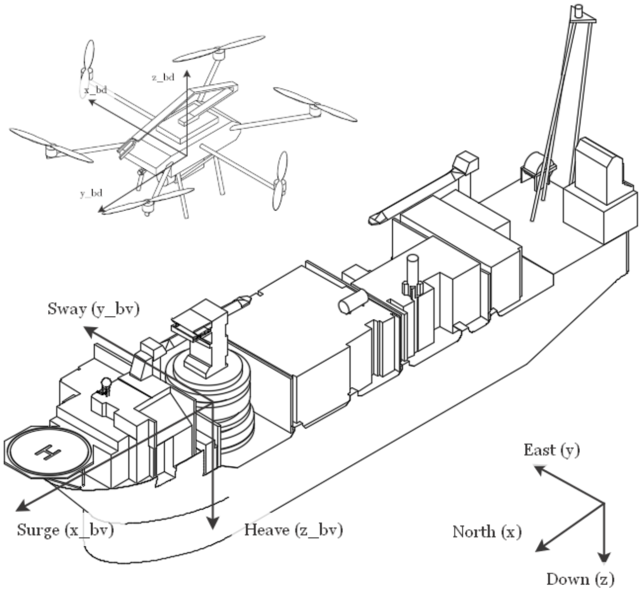

Figure 15: Frames of reference (*objects are not in the same scale*)

The operational environment is an offshore aerial inspection of a vessel. So, it is our primary object of interest, thus all intentions performed by drones must be done according to its position and orientation. One of the key points here is to define position of the vessel's body-frame origin, because there usually three frames that are considered for marine vessels [102]. One of the FPSO's features is that they are anchored by use of turret mooring system, such that the vessel can freely rotate 360°around its pivot point, which is the turret. To be able to calculate motion of the drones around vessel we need two frames – body-fixed frame of the vessel itself and body-fixed frame of the drone. To minimize the computation and attitude determination errors (which can potentially lead to crashes), we will use the relation of the body frame of drone to the body frame of FPSO instead of NED-frame (North East Down) (Figure 15). Usually, origin of the vessel's body-fixed frame located in the CG (center fo gravity), such that its axes coincide with the principal axes of inertia to simplify equations of the motion. In our case, it is easier to "move" the origin, so the z-axis coincide with the center line of the turret.

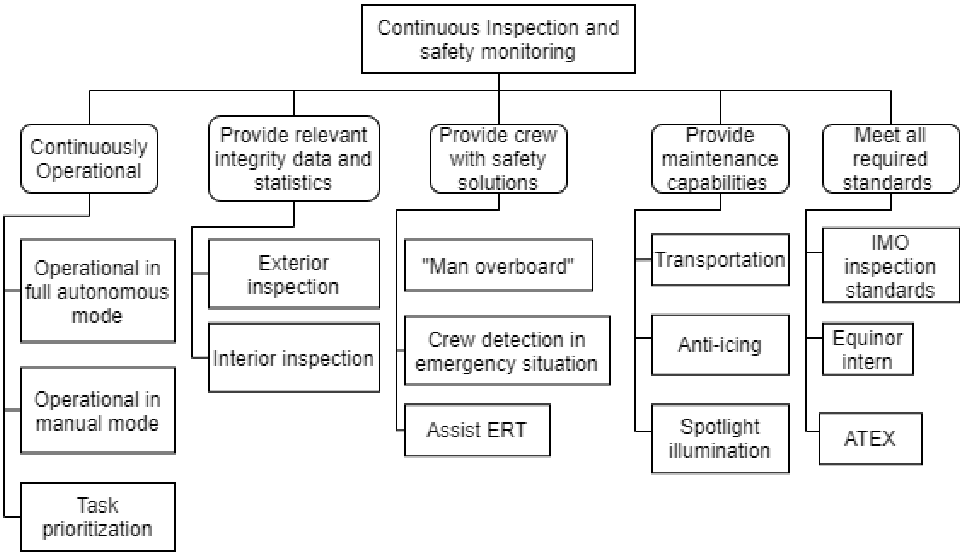

Figure 16: Objectives tree

4.4 Concept Definition

Before we go to concept architecture and structure of its components, it is important to summarize the key features and terms for the entire system. Due to lack of the required regulations, we will base on the existing information/regulations, allowing to make some assumptions.

Objectives that are planned (use-case scenarios) and basic standard requirements in schematic form can be seen in Figure 16.

Since we want to implement this automated inspection system to enhance already existing inspection techniques and reduce risk of injuries, we need to set up the requirements that should be met [22][103]:

1. The results of remote inspections, that are normally manually acquired by surveyor, should be on the same level of detail or better;
2. System should be operational 24/7, with respect to weather conditions, safety
3. Sensing data should be obtained, transmitted and stored (archive) in a safe manner;
4. Acquired data (images, videos, sensing data) should be available to the end user (surveyor) for presentation and other use (processing)

5. inspection data that contain personal data, should not be collected nor used contrary to existing data protection and privacy regulations (e.g General Data Protection Regulation);
6. Inspections, data interpretation, drone operations (control) and their maintenance should be done by qualified personnel
7. inspection data should be marked such that it is always possible to determine place and time it was collected;

The term "operational 24/7" means that drones are ready to be deployed in few minutes, or so long it takes to create new or update existing flight plan, in case of emergency. Since there are limitations today that make it problematic to perform automated inspection of the cargo holds, this type of inspection will be performed in manual (semi-manual) mode at the beginning. Considering that the main idea is to get the fully automated system, for now we will discuss intentions and set-ups related only to "outdoor" flights (use-case scenarios). When the technological and regulatory gaps will be covered, the interior use-cases can be easily integrated into the system.

4.5 Preferred System Architecture

A fundamental setup of each manual or autopilot mission architecture can be seen in Figure 17. It consists of three subsystems: Mission Definition System (MDS), Pilot App, Drone. Despite the fact that the goal is to have fully autonomous system, we include the possibility for pilot to take manual control or retarget drones without causing their "disorientation".

Mission Definition System:

First, we will discuss how we can set up missions that can be pre-planned, i.e. exterior inspection and environmental monitoring scenarios. Each use-case scenario consists of relative sub-scenarios. For example, exterior inspection is defined as set of smaller (sub-scenario) missions, as can be seen in Figures 18 and 19.

To optimize the calculation of drone's flight logic, each sub-mission is represented by a set of waypoints. A single waypoint is a 3D coordinate, which drone must reach. These waypoints (as single point or set of few) represents a point of interest (POI), where drone will perform some type of inspection. For the pre-defined scenarios, each waypoint (or resulting path) also contains details about drone's intentions. This information describes orientation of drone/gimbal, cruising speed, hovering period, etc. All these

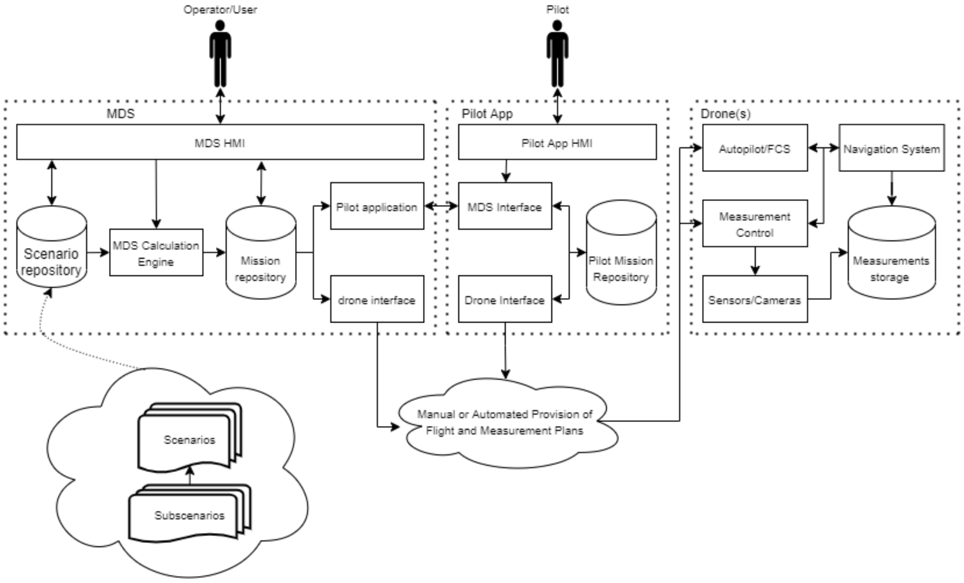

Figure 17: System setup [9]

setups are stored in the "Scenario repository" and can be accessed by operator/user via "human-machine interface" (HMI). It will allow to add or make changes in missions.

Based on the inspection schedule or by demand, we manually (or automatically) pick up some of these POIs. List of these points presents the scenario for the specific day. After this list is generated, it passes to the Mission Calculation Engine. This engine is the core of the entire system and plays key role in overall success. Here, the flight and measurement plans being calculated with respect to mission specifications, expected drone's dynamics, weather conditions, number of involved drones, etc (Figure 20 [9]). When flight plan is calculated, it is being sent to mission repository, which stores all information related to the specific mission, to the pilot app (to be accessed in case of manual flight or interruption during autonomous flight, if needed) and to the drone(s).

Such reports need to be created and approved at least 12 hours before any flight intentions for each day, when there are planned drone operations [52]. This plan should include:

- Purpose of the flight
- Risk assessment

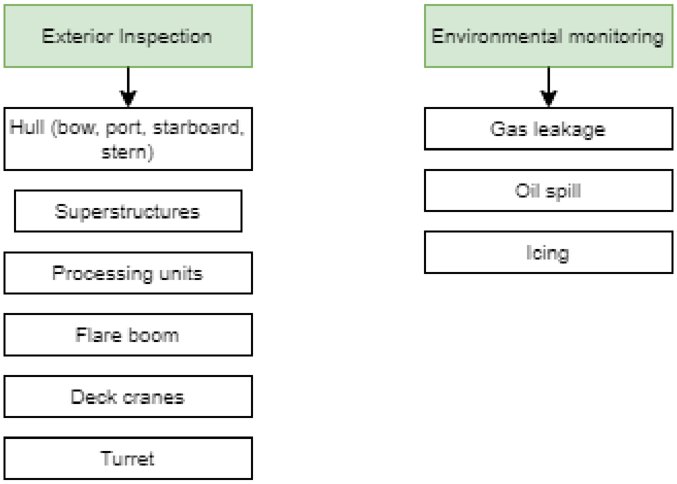

Figure 18: Setup of Mission Repository

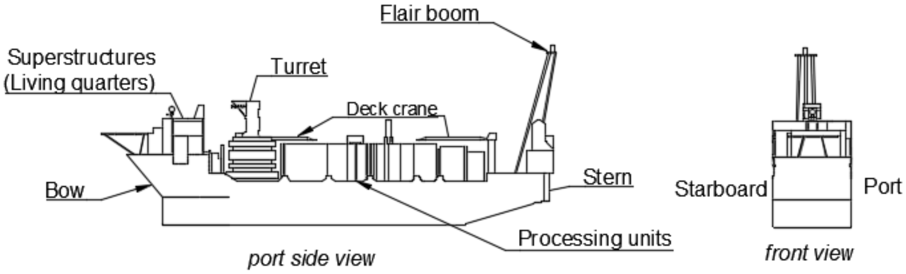

Figure 19: Vessel structures that are of interest for inspection

- Assessment of if additional necessary equipment or actions are needed (placing barriers, using of observers/assistants)
- List of instances that needs to be informed about operations:
  - Operational manager [9]
  - HLO
  - HFIS
  - all instances/vessels equipped with helicopter (flight) deck within 5NM (9,26km) radius

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[9] In Norwegian: Operasjonelt systemansvarlig

- Overview over areas where flight will be performed:
    - Flight path
    - Take-off and landing points
    - Altitudes
- Overview of simultaneous activities (e.g. cranes, helicopter traffic)
- Handling (intentions) of the drone(s) in case of alarm situation

Also, based on the fact that all inspection actions are pre-planned, upon the requirements from maritime organizations, internal regulations or manufacture's, flight plans do not need to be set up before *each* flight. On later stages of the automation, these plans may be created and approved automatically, using artificial intelligence. After approval, warning massage will be distributed automatically to the relevant instances (see above). All these plans should be stored in "Mission repository" and be accessible by end user. After flights are completed, repository should be updated with all collected data, so *all* information related to specific mission is stored together in one place.

Mission Calculation Engine

This is the core of the whole system. We can say that is the most complicated structure as it should calculate the desired flight plan based on multiple input variables. First, mission specifications (list of intentions) are converted into the flight plan with respect to inspection patterns. These patterns present sets of instructions or rules which defines path of a drone according to area or object of interest and specifications of sensing equipment. This flight plan is a set of waypoints relevant for the specific inspection mission. After that, this plan being divided into set of the instructions - scripts, that will be executed by drone(s). They also define the behavior of the drone that is needed to perform necessary measurements, such as hovering on specific coordinates with required orientation (like yaw angle) during time interval that is needed. Further, this set of instructions is sent to Trajectory Integration unit, which calculates the trajectory with respect to presenting weather conditions (WM-wind model), drone's aerodynamic and physical model (APM-aircraft performance model). This simulated trajectory is relevant for visualization of the drone's intentions. Such simulation not just ease the planning of inspections, make all involved actors to share a common view, but also allows to make a visibility/safety tests. Furthermore, it will provide relevant information, needed to fill into the flight plan report.

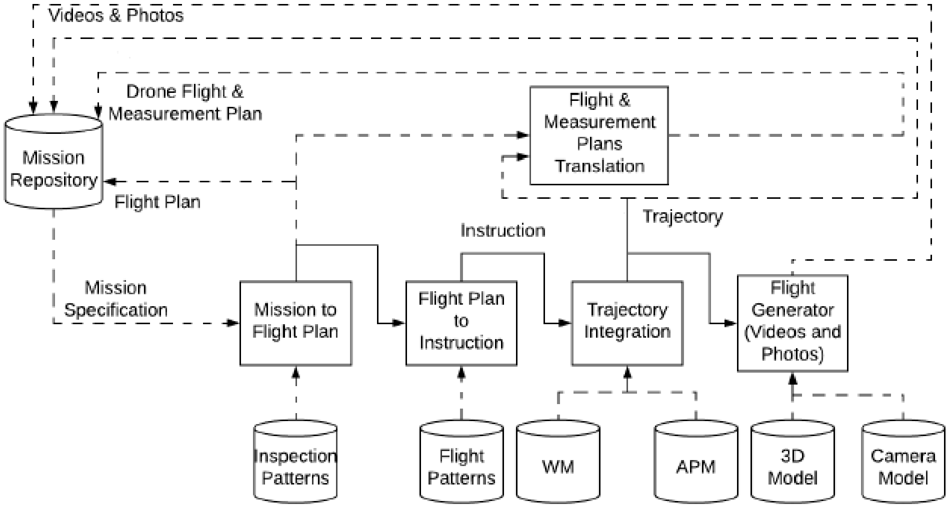

Figure 20: Mission Calculation Engine[9]

Finally, the flight plan and calculated trajectory are being uploaded to the drone before the flight.

Pilot App

Pilot App provides all necessary information and specifications of the mission that are needed by pilot to perform a flight and/or take measurements manually. It will also allow to interrupt the drones' intentions and take manual control over it or change the mission. These missions are stored and accessible from the "Flight mission repository". Since significant changes will need change of the flight plan[10], it contains set of rules of allowed interruptions in the scenario. For example, if the drone performs inspection of a specific point, but we want to inspect the spot few meters away (what could be allowed in this situation), we can add that specific waypoint to the path. This also means that path planning algorithm should be able to recalculate the path "on a fly".

Taking into account that while emergency situations can be similar, they can vary in "screenplay". So, automated set up of the drones' flight path can be complicated or even impossible in some situations. In a critical situation each second counts, so the time reduction between sending a request from emergency response team (ERT) and drone action is important. In a highly automated system, we can reduce the chain of supervising and executing to a minimum by allowing the ERT captain (or assigned team member with

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[10] what is strongly not recommended because in worst case it will lead to mission abortion

relevant skills) manually guide the drones via "pilot app" (or ERT alternative). In case of a situation when there are no defined waypoints, that person can manually define script: choose drone(s) and "draw" a path and desired viewing angle of cameras. These data can be entered via individual tablet or PDA. This feature can be part (integrated) into the general emergency response system. It will allow fast sharing of relevant information between participants (response team(s) and their members), observers and external actors. Similar approach being used for firefighting [104] and as infantry combat system in military [105].

In case of such interruptions and manual control, additional software solutions have to implemented. Its role is to automatically control drone(s) between manual inputs (when UAVs are "standby"), automatically reassign tasks between if one of them needs recharging or loses control. Because of its complexity, we can not fully relay on simple "if-else" statements, so decision making and executing AI capabilities needs to be implemented.

Drone interface system

The third subsystem is the drone interface system. The flight plan's instructions being passed to Flight Control System (FCS) and converted to formats that are understandable by drone's onboard computer. Based on the mission requirements, Measurement control unit is responsible to take measurements at desired positions. Navigation system should not only provide solution for navigation, but also ensure time-stepping of the sensing samples to georeference obtained data.

4.6 Concept Exploration

In this section we will discuss overall setup and data flow which is shown in Figure 21.

Idea is to get a fully autonomous system, that will act independently from operator. To achieve that it is necessary to find set up the flow chart that will describe the general workflow. Proposed solution can be seen in Figure 21. It consists of several loops: initial (preflight or standby), flight plan calculation "side loop", scheduled task execution and emergency.

In flight plan the mission for a day being calculated as been described earlier. It is based on list of scheduled, manually entered or those that are remaining from previously interrupted (because of weather change, emergency, or other reason) inspections. During preflight, drones are stationed on their landing pads in standby mode and are ready for takeoff in case of emergency or in manual (after flight plan is uploaded) or automatic mode. At highly autonomous setup the manual mode is planned to be used only in

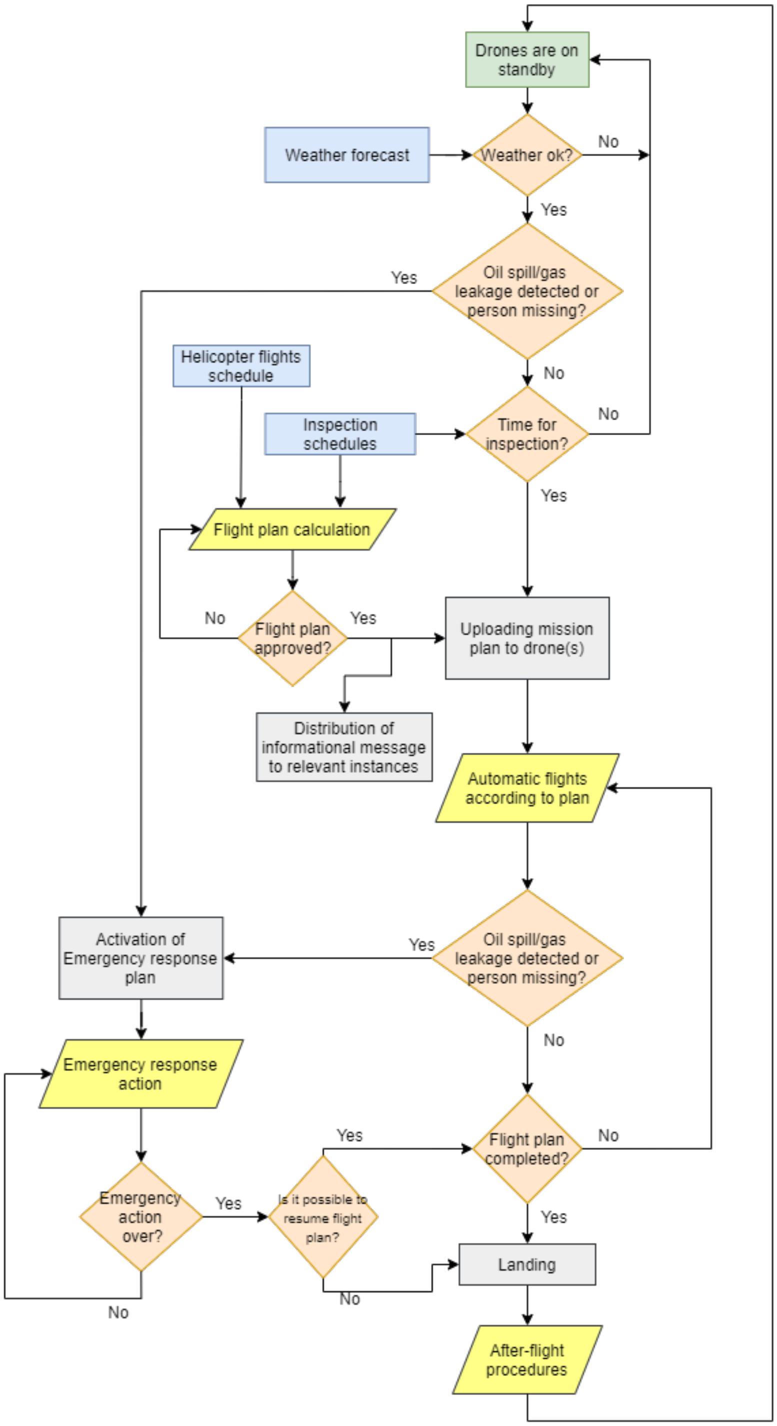

Figure 21: Overall flowchart

cases when unforeseen situation occurs, when drones are *already* airborne. During emergency or if any other path corrections are needed, they will be entered "graphically" or by choosing from a predefined list. In other words, pure manual control is reduced to a minimum. This loop is divided into three sub-loops: weather check, emergency awaiting and check for inspection schedule. If weather is bad (e.g.it exceeds drone's limitations) there will be no flights anyway, so this is a first check that might be done. When weather is good, drones are staying alert for possible accident. If something happens, it "activates" emergency protocols - uploading of "emergency scripts" to drones, then takeoff of all required drones and further work under ERT control. If there is no emergency, we check for inspection schedule. If there is planned inspection intentions, mission plan being uploaded to drones, if there is nothing for a specific day - UAVs continue in standby mode. These emergency protocols (list of intentions) can be also stored in drone's internal memory in case of communication degradation.

After plans are being uploaded, UAVs perform actions specified by mission's instructions, while continue monitoring for critical situation. During flight, collected data being transmitted to "ground station" where it being processed in real time. This is done to get a warning about detected anomaly.

There is also needed to have a hierarchy of missions, so it would be possible to automatically switch between mission on a fly in a situation when there is need to interrupt the task in progress with on that is more important to be performed at a moment. Most naturally it will be situations when we will need to initiate a "search and rescue" operation when some inspection is in progress. If it occurs (especially when person is missing) - all ongoing actions being aborting, rerouting according to emergency scripts. To be able to continue inspections later from a breakpoint, it is desirable to automatically register every drone's action in a flight log. When all planned intentions are fulfilled, drones returning to their stationing positions and performs after-flight actions - de-icing, recharging, drying and others.

4.7 Autonomy levels

In simple words, automation level describe the replacement degree of human by computer. Its gradation is ranked from *Low*, where all no computer decision making system is involved and everything is performed manually, to *High*, where no interaction from operator's side is needed, as can be seen in Table 6.

According to performed literature study, there does not exist any automated inspection of marine vessels solutions today. All actions are done

Table 6: Autonomy levels gradient [17]

Extremes	Gradation level and description
Low	1. No assistant from computer, human takes all decisions and actions
	2. Computer offers several alternatives (no decision making)
	3. Computer narrows alternatives down to a few
	4. Computer suggests recommended one alternative
	5. Computer executes suggested alternative, if human approves it
	6. Computer executes suggested alternative, human can veto
	7. Computer executes suggested alternative and informs human
	8. Computer executes alternative and informs human only if asked
	9. Computer executes alternative and informs human only if it decides to
High	10. Computer decides and acts autonomously, ignoring human

manually, so we can say that offshore we are on *level 1.* There are some projects that works on inspection of power lines and buildings where drones flights along path defined by manually chosen waypoints. As we can see, concept of autonomic inspection is quite new and lacks some techniques on the market. So, the good starting point is in step-by-step automation, where we have possibility to practically check effectivity of the implemented processes and if needed fix defects/bugs as same as simplify on a fly. It can also help to define regulations, guidelines and outline further recommendations.

When we are talking about autonomy, we mean that the drones not only performs flight on predefined path, but do it based on the required set of tasks and scripts. The flight plan being calculated automatically according to predefined set of rules and passed to the onboard data handler, then drone performs takeoff and proceeds along the desired flight trajectory making relevant sensing. Collected data then being sent to the “ground station” and processed there, what will give much faster computations. After fulfilling the required tasks, drone returns to the base for charging and making necessary procedures (prepares for the next flight). All processes happen without any interruption from the operator’s (user’s) side. Operator’s role in this case is to monitor the overall status of the whole system, intervening only if unintended situations occur or any extraordinary tasks should be performed manually. Basic requirements for the autonomy of the system can be derived as: "Automated:

- scheduling,
- path planning (3D path planning),

- deployment,
- sensing,
- collision avoidance,
- charging."

At first stages we can start from automation of processing of collected data and automate piloting algorithms later, which will allow us to fix possible bugs. Otherwise, we can get situation, when flight logic will command to move a drone to next waypoint while collected data had disturbances or computer did not get enough time to transmit/process all data. When image processing is in place, we can start to implement navigation along manually predefined waypoints and routes. It will allow to test navigation algorithms and its combination with image processing. It is preferably to start with automation of outdoor flights first, due to difficulties in navigation inside cargo holds and ballast tanks. Also, even though there exist solutions for semi-auto and auto flight solutions *onshore*, there does not exist any autonomous solution for marine operations. So, testing of control laws and equipment is needed.

Automatic inspection of ballast tanks and cargo holds is set to last stages, because for now it is not possible to implement automatic deployment (flight from and back to landing pad) due to lack of regulations and existing technical limitations.

Summarized steps for autonomy implementation ("autonomy gradient") can be seen in Table 7. Where by "Outdoor" we mean flights performed outside of FPSO (external inspection) and by "Indoor" - inspection of cargo holds/ballast tanks.

At first stages it is better to have crew of two members: one is responsible for maintenance, technical assistance, piloting and another one who can interpret collected inspection data, take care of sensors. At high autonomy levels, almost all functions will be done by computer, so the role of operator will be in monitoring ongoing processes and act only if computer will not be able to resolve situations by itself. He will also have a responsibility for maintenance of drones.

4.8 Landing pad design

Beside of the drones, landing pads will play an important role in maintaining system performance. On the earliest stages there is no need for "own" base,

Table 7: Autonomy implementation gradient

Step	Flight autonomy	Inspection autonomy
1	All manual	Transmission of inspection data to computer with manual processing
2	—"—	Automated image processing of optically collected data, no use of manipulator
3	Outdoor: semi-auto (auto following of manually set up waypoints/routes) Indoor: manual	—"—
4	Outdoor: Auto scheduling + same as in pkt 3 Indoor: Implementation of navigation algorithms. manual "flight in"	—"—
5	Outdoor: auto deployment Indoor: semi-auto (auto flying, bringing of drones inside tanks/holds) by hand	—"—
6	Implementation of drone control from ERT tablet	—"—
7	Outdoor: fully auto flights for inspections Indoor: Implementation automatic deployment	same as pkt.1 plus use of aerial manipulators

since they are manually operated, operator can easily bring the drone with him by hands. But on later stages, when we will implement automatic operation of several drones, UAVs will need a separate landing and storing solution with multitasking capabilities. This types of landing pads solutions are called "drone in a box" (DIB), used for stationing of autonomous drones.

It is made if a form of a "box" where UAVs being stored and where basic drone's maintenance is done. Beside of "just storing" and protecting drones from external impacts (as for example weather), we want it to be able to do simple service functions. The required minimum of such services is the ability to recharge drones. To increase drone's maintainability and significantly reduce charging time, it will be better if there would used replaceable batteries. It will definitely raise the problem of implementations of such mechanism, especially with respect to drones positioning on that pad, and not to forget ATEX problem, because there could easily occur sparks. But when implemented it will let a drone to be ready for flight within seconds. Another problem, that we will face with flying during cold periods - is icing of a drone's blades. It is a significant problem that leads to drag increasing which results in reduced lift and maximum angle of attack (that is important for speed control, stability controllability) [106]. So, additional system for ice and moisture removing is also necessary. It can be outlined in two ways - integrated into drone's structure or be a part of landing pad. For higher productivity it is better to have both, so we can remove ice coating that is critical for flight and secondly remove icing occurred on drone's parts which is not covered by integrated solution.

For fixed-wing aircrafts there are proposed several solutions of integrated de-icing methods: electrothermal, mechanical (pneumatic) and chemical. Pneumatic system is presented by inflatable rubber boot on leading edge surface of the wings (Figure 22-a). If icing is detected, boots being inflated with air causing breaking of ice. While being used on small aircraft (e.g. Beechcraft King Air series [107]), they are not practical to be used on a small UAV, because of their complexity and high weight. Another alternative is to use liquid anti-icing chemicals prior to flight. A drawback of this method is that chemicals can potentially damage sensors or optics. Also, efficiency of the chemical agent can be reduced during flight as water can dilute it. Use of electrothermal (Figure 22-b) looks promising as it is a highly effective and lightweight solution that can mitigate risk of icing [11]. However, energy efficiency of such thermal system is quite challenging, as it can consume high amount of energy. One of the ways to reduce consumption is to heat surface periodically (in cycles). This means that we will be able to implement it on a fixed-wing UAV, but not on multirotors. Instead of installation of active deicing system on a small drone, which is challenging, we can use combination of sensors and artificial intelligence to detect ice accretion before it poses a danger. It can be formed by a subsystem that uses atmospheric sensors (to "read" current weather conditions[11]) in combination with thermodynamic principle of the surfaces and continuous monitoring of drone's aerodynamic behavior. Additionally, using icing conditions with current weather and forecast we can "predict" accretion and therefore expand flight plan with periodic landings for de-icing. All that means that we need to have additional de-icing system integrated into the landing "box". Beside of the capability to remove ice, wet snow, water, it should be powerful enough to do it during short landings between flights. It will be also important to remove ice quickly during emergency situations.

If several types of UAVs will be used (combinations of multirotors and fixed-wing), there will be a need to use different types of landing pads. Since fixed-wing drones will not be used for close-up inspections, but rather for general overview and during emergency situations, there is no need to have complex solution for its storing. It is also possible to say, that they are not actually *landing* pads, but *take-off* pad (i.e catapult), which is not suitable

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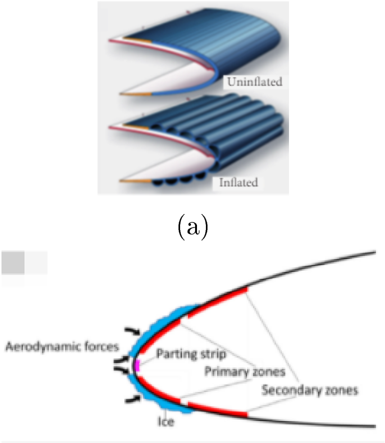
[11] they can be used as "stand alone" icing detection system, but it will not have high precision rate



(a)

(b)

Figure 22: (a) Inflatable rubber boot [10] and (b) schematic layout of the heating zones [11]

for landing. But for simplification and to avoid confusion, the term "landing pad" (LP) will be used for both types of "storing boxes" for both types of drones.

To minimize risks for damaging multirotors during take-offs and landings, self-balancing landing platforms can be used. Its role is to counteract movement of FPSO to keep the landing zone (where touchdown and lift off is performed, see Figure 23). Such a mechanism will increase the complexity of the LP and it also can be difficult to seal the gap between touchdown zone and housing, hence there is chance for salted seawater to penetrate inside and damage electronics or servos.

Based on what has been discussed above, we can set up two types of LP, see Table 8. Example of the possible LP for multirotors can be seen in Figure 23. It will contain:

- Anti-icing solution – to remove ice and snow from drones
- Firefighting solution
- Battery replacement arm – to change batteries
- End effector cleaning solution – to remove couplant from sensors
- Battery charging station and end-effector storing compartment – idea is that end effector will be changed automatically according to mission

needs

- Separate storing/charging compartment cover – to isolate section from snow/water and insulate rechargeable batteries

Table 8: Landing pad specifications

Drone type	Landing pad description	LP' integrated functions
Multirotor	formed as "storing box", capable for both take-off and landing	Charging, anti-/de-icing, end-effector cleaning and changing, self-stabilizing platform
fixed-wing	catapult ⇒ launching only	pre-flight charging and anti-icing

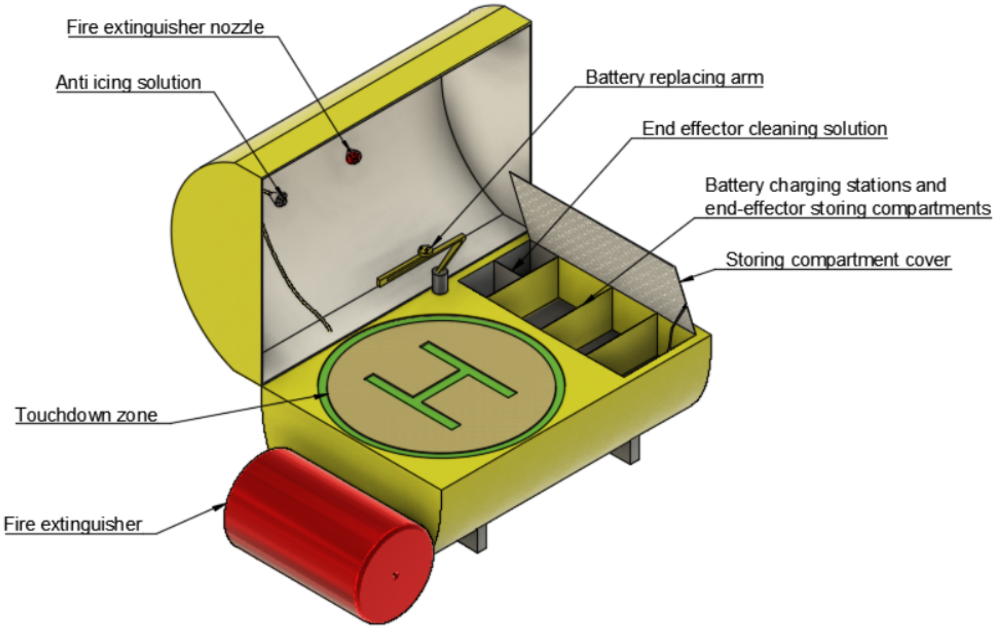


Figure 23: Example of multirotor' landing pad (LP)

5 Framework

5.1 Fleet configurations

Based on specifications of missions' and drones, it is now possible to propose a setup of fleet of drones. Use of number of drones of various type will allows to do different tasks simultaneously, thus ensure continuous flow and coverage. Use one or two drones for all tasks is also possible, thus it will reduce costs, but they will not provide sufficient flow (continuity and coverage) of inspections, in other words effectivity of such use will be low. Another factor is energy consumption – having a single drone that will need to cover bigger areas will result in non-optimal power consumption, due to raised amount of deadhead="worthless" flights. While swarm of drones will be able to cover more tasks on the same battery capacity.

To be able to propose optimal minimum number of drones, we need to see at frequencies of use-case scenarios (Table 9). As we can see, the most common proposed scenarios are related to outdoor flights, what means that we can focus mainly on them. Out from drones' classifications, we can see that for our needs we can use two types – fixed-wing and multirotors, what gives two possible main configurations:

- Multirotors only
- Combination of Multirotors and Fixed-wing

Due to high efficiency in prolonged flights, fixed wing can be used for search-and-rescue operations and pollution monitoring. Due to low probability of these missions, there is no need to have more than one of them. If case there will be need to have additional monitoring drones, then we can use mulitortors.

To reduce complexity of path and scheduling calculations we can use the concept of "one zone-one drone", which means that we divide vessel into several zones where only one drone of specific type will operate at a time (such that we will not have two, e.g., "maintenance" drone in one zone at the same time). Natural way for such division is to use vessel's sides: Bow–Stern–Starboard–Port (Figure 24). To assign specific multirotors ("scout" or "maintenance" – see Table 9 -"Drone's functionality and specs.") to each zone, we need to see what kind of tasks will be preferred in these areas. Due to lower battery consumption of "scout" drones, they can be placed at Port- -Starboard sides, and "maintenance" drones can be placed at Bow–Stern sides (Figure 25).

Table 9: Proposed regularity of tasks and drones that could be used

Regularity	Mission (UC)	Drone's functionality and specs.	Drone types
High	Outdoor: overall survey, pollution monitoring	*"Scout" drones* with optical sensors and simple grippers to transport lightweight objects	Multirotors
	Outdoor: close-up survey	*"Maintenance" drones* with aerial manipulator	Multirotor
	Indoor: ballast tanks	Small collision tolerant (w/ protective cage) scout drones*	Multirotors, possibly underwater "snake" robots
Low	Indoor: cargo holds	Collision tolerant: "Scout"(w/protective cage) with optical sensors; "Maintenance" (w/ propeller guards) with aerial manipulators and optical sensors	Multirotors
Very rare**	Outdoor: search and rescue "Scout" drones	Long flight time	Fixed-wing, multirotors

**use of aerial manipulators not possible if protective cage being used*

***these missions are not predictable, so they are out of "Regularity" classification, assuming them to be "very rare"*

This configuration of total four (+1 eventual fixed-wing) can be reduced to only three drones – two "scouts" (takes Bow and Stern sides) and one "maintenance" (which will cover both Port–Starboard sides). There is possibility to make such reduction in number of "maintenance" drones, because frequency of tasks related to contact-based samplings will be low because vessel is newly built.

Further reduction in undesirable, because then it will not be possible to optimally distribute tasks and we can end up in unbalance of costs–performance relation (drone will use more time to fly back and forth for recharging than for actual inspections).

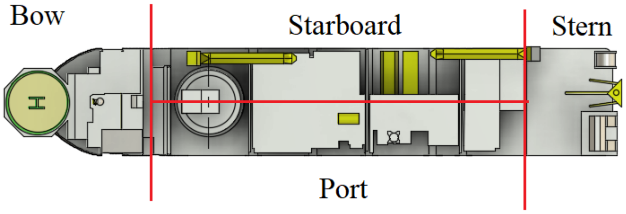


Figure 24: Bow-Starboard-Port-Stern zoning

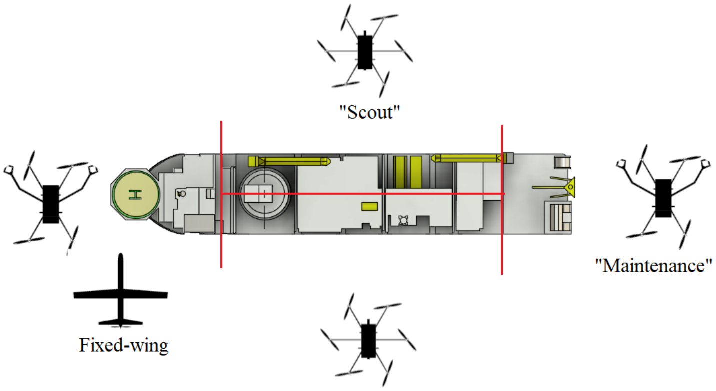


Figure 25: Example of drone configuration

Drones that will be used for indoor inspections stays a little bit aside due to their characteristics – to be able to fly inside ballast tanks and cargo holds they needs to be in small size, because of restrictions of manhole-sized hatches and what is impossible due to existing regulatory and technical restrictions. What means that drones need to brought there. Additionally, frequency of such tasks is very low, so there is no need for more than two (or one, if use of protective cage will allow use of sensing end-effectors).

In view of the foregoing, we can set up the table of proposed optimal fleet configuration – Table 10.

5.2 Flight logistics

Flight logistics establish and describe motion and interaction of all involved drones. Depending on how well it being organized, the overall effectiveness

Table 10: Proposed fleet configurations

Type of drone	*Operating area and function*	*Minimal quantity*
Multirotors' fleet		
Multirotor: "Scout"	**Outdoor**, visual inspections, pollution monitoring, search-and-rescue	2
Multirotor: "Maintenance"	**Outdoor**, visual inspections, close-up surveys (using aerial manipulator), transportations	1 (2 recommended)
Multirotor	**Indoor**, visual inspection, close-up inspection (using propeller guard or protective cage that would allow use of aerial manipulator)	1
Combined fleet		
Fixed-wing	**Outdoor**, search-and-rescue and spill monitoring	1
Multirotor: "Scout"	**Outdoor**, visual inspections, pollution monitoring, search-and-rescue	2
Multirotor: "Maintenance"	**Outdoor**, visual inspections, close-up surveys (using aerial manipulator), transportations	1 (2 recommended)
Multirotor	**Indoor**, visual inspection, close-up inspection (using propeller guard or protective cage that would allow use of aerial manipulator)	1

of the inspections and monitoring may vary. It consist of several parts:

- Automatic scheduling - continuous operation and coverage
- Path planning - calculating of optimal flight trajectory
- Collision avoidance - safe flight
- Navigation - provides point-to-point guidance information or position data

5.2.1 Automatic scheduling

To ensure continuous flow of the inspections and monitoring, it is important to solve the scheduling problem. It can be defined as a determination of an optimal allocation of inspection and monitoring tasks to fleet of drones, while minimizing the overall costs, which consist of “deadheading” flights between tasks. Implementation of scheduling is quite challenging because operation of a UAV if often deviate form the schedule due to uncertainties [12].

Scheduling of inspection drones is very similar to scheduling public transports (PT), where they also need to deal with similar inputs and conditions [108]:

- set of vehicles (in our case - drones) revenue trips to be operated, characterized by:
    - starting point and time
    - ending point and time
- possible *layover arcs* between the end of the trip and the start of a later trip at the same location
- possible *deadhead arcs* connecting:
    - depot (in our case - landing pads) to trip starting point, also known as "pull-out"
    - trip from ending point to depot (e.g landing pad), also known as "pull-in"
    - trip ending points to trip starting at different location (point)

In this project we are operating with predefined inspection/monitoring paths, so simple duty cycle of a single drone is presented as chain of predefined events connected by deadhead and layover arcs (Figure 26). Schedule can be

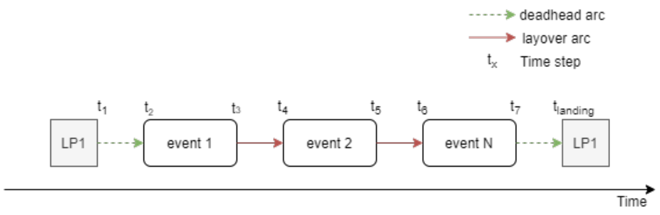


Figure 26: Simple duty cycle for one drone

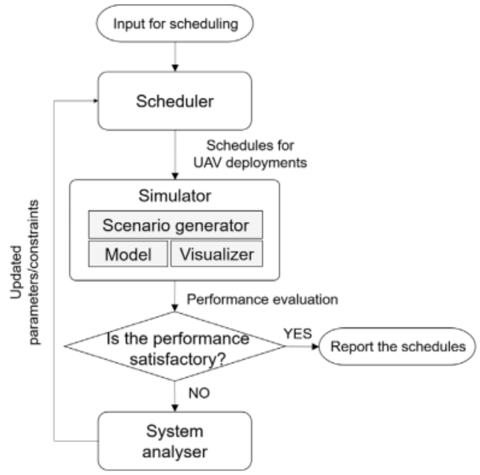


Figure 27: Simulation-based scheduling system framework [12]

generated by "Mission Calculation Engine" during mission calculation, which generates flight plan for mission with respect to physical models. Same approach for "Simulation-based scheduling framework" being proposed in [12]. Just like the "Mission Calculation Engine", it is based on "scenario generator – simulation model – visualization" architecture (Figure 27). Solving the Scheduling problem consist of two steps:

1. Determine events, sequence and assign UAVs
2. Path calculation to guide UAV along sequence and avoid collisions

Sequence of events being calculated by Genetic Algorithm (GA). First, randomly picked events forms a chromosome, sequenced as integers from 1 to N (total number of upcoming events). Then, this chromosome being divided between drones with respect to their "time windows" (time that drone can spend in the air). Example of division of a chromosome, that consist of 10 tasks (events) can be seen in Figure 28. Time windows can be calculated based on mean power consumption of the drone and weather conditions, where temperature and wind strength are main values. How many tasks can be carried by drone on a single battery capacity can be found by summarizing time required for each event (we know it, since specifications of most planned events are known in advance) and time required for deadhead/layover arcs. After that, GA generates several populations and finds the best sequence division for each drone respectively. If we use the zone division principle, then it makes it easier, as we do not need to assign a sequence of *all* events

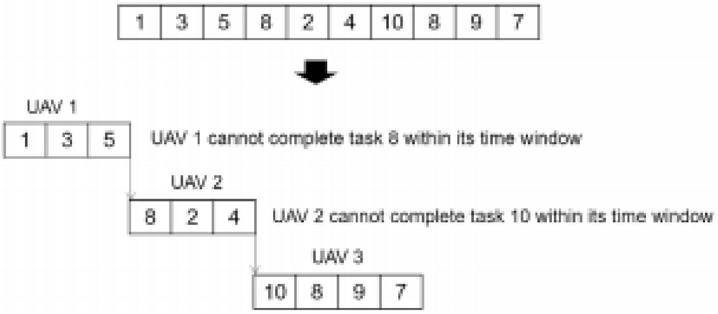


Figure 28: Division of randomly generated GA chromosome [12]

to *all* available drones each time we want to perform inspection. It is already divided by zones to belonging drones, so only sequence of executions has to be calculated.

When it comes to scheduling of the indoor events, than it becomes slightly different, as it is not possible to fly inside (and will be not feasible in foreseeable future). Here, before implementation of autonomous flight in/out, simplified scheduling will be used - generates timetable that contains only *what* and *when* have to be inspected.

Scheduling algorithm which will be used, have to be flexible in a certain way: if there happen any unplanned situation which causes abort of action, following functions are needed:

- Schedule adaptation - in accordance with the occurred situation. So the drones will continue to perform their tasks in a place where interruption occurred and schedule will be updated respectively to delays

- Schedule extension - in a situation, when tasks can not be resumed after unexpected case is over, there should be possibility to automatically update the upcoming schedule with resting tasks.

5.2.2 Path planning

Path planning has an important function to ensure optimal collision-free path in complex environment. Due to different trajectories required in use-cases, there is need to use different approaches for path calculations – in situations when drones will fly in complex, obstacle rich (clattered) environments (e.g. transporting items within the ship) it is required to use more advanced 3D path planning algorithms. In other situations, as for example inspection of the hull or flying with constant attitude, 2D algorithms can be used.

For inspection missions we will use a set of pre-calculated patterns (waypoint sequences) for each individual inspection task. Basic inspection patterns usually present vertical or horizontal strips (so-called zig-zag method) to inspect flat surfaces, spiral (cylinder) and Archimedes spiral for curved surfaces [19] (Figure 29). In this case, main task for path planning algorithm is to optimally connect the takeoff point with the starting point of the first inspection pattern, after that navigate the drone along inspections trajectory then connect the ending point of the first inspection pattern with starting point of next pattern and so on till the connection of the ending point of last inspection pattern with landing point (this flow is like scheduling timings in Figure 26). To be able to use simpler 2D path planning algorithms, there is need to split the 3D pattern into sequence of 2D paths and use additional waypoints that will "connect" them together and navigate the drone around obstacles. All these waypoints will form a node (waypoint) grid (Figure 30). Using that approach gives possibility to use simple heuristic algorithms that are based on the finding of the shortest way between waypoints. Results shows [109] that among eight most popular algorithms [12] MILP (Mixed Integer Linear Programming) algorithm shows most sufficient results in reasonable computations time compared to traditional A* or Dijkstra's. While Genetic Algorithm, Potential Field and MSLAP are more effective relative to computation time, their main disadvantage is that probability of non-optimal path results rises in accordance with number of nodes (waypoints).

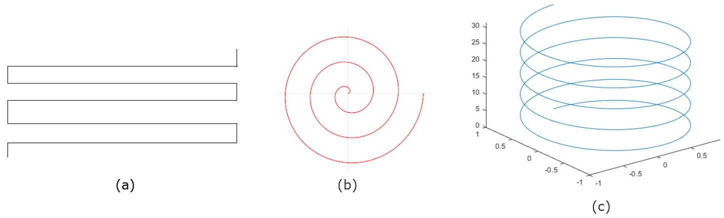

(a)
(b)
(c)

Figure 29: Basic inspection patterns: (a) strip method (b) Archimedes spiral (c) spiral

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[12] Potential Field, FLoyd-Warshall, Genetic Algorithm (GA), Greedy Algorithm and Multi-Step Look-Ahead Policy (MSLAP), A*, Dijkstra's, Approximate Reinforcement Learning (RL), MILP

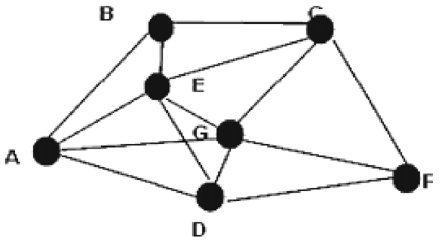


Figure 30: Simple waypoint grid [13]

5.2.3 Collision avoidance

During automatic flights along calculated paths or in manual mode, we can face with problem of possible collisions. Ability to detect obstacles in time and avoid them is probably the most important feature of the drones. It should handle uncontrollable weather impacts and non-constant light intensity and ensure safe operations under different external conditions.

By *collision* we mean not the actual crash, but when distance between drone(s) and an object is less than the determined threshold (collision radius). We can check if that threshold being violated by calculating the difference between position vectors of a drone and object ($\vec{r}_d$ and $\vec{r}_o$ respectively) and compare it to the collision radius R_c 1 [14]:

$$\|\vec{r}_d - \vec{r}_o\| < R_c \tag{1}$$

What simplifies the collision avoidance system is that we operate in a know area, where locations of majority of the obstacles are known. So, we can divide the collision awareness based on the obstacle types, in following way (Figure 31):

During path calculation phase, we can already see if there will be any possibility for path intersections or they will be in proximity from each other. To reduce chance for collision with stationary obstacles already during computation stage, we can use following rule: *nodes presented by intersection of paths or areas where several paths go close to each other, as same as defined "safe" area around such locations, can be occupied only by one drone in a time.*

To avoid "idle" hovering while waiting for these nodes to be available, the schedule must be set up such way that drones expected to visit these places in a different time windows.

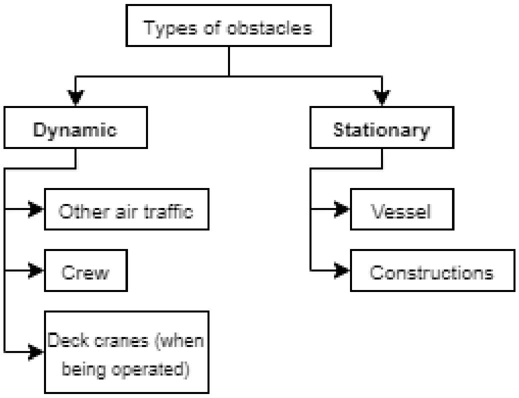


Figure 31: Example of obstacle gradation

If one or several drones being operated manually at the same time when there are drones under automatic flight, we can use following approach: we define a "no-fly" zone with certain radius around manually operated drone, which cannot be accessed by drones in automatic flight. This is probably most relevant during early stages of automation, because the "pure" manual control is proffered to be avoided as much as possible, whereas the "semi-manual" will be used.

To avoid dynamic obstacles additional techniques with more restrictions are needed. Flow of the collision avoidance process consist of several stages (or steps): *Sense*→*Detect*→*Avoid*, Figure 32: At first stage we use sensors that are installed on the UAV to sense the certain surrounding area. There are two types of sensors that can be used for that - active and passive. Difference between them is that active sensors both emit and detect reflected electromagnetic radiation, while passive only measure reflected one. When some obstacle being detected, computer calculates the probability of collision. Based on these calculations, the Collision Avoidance system compute and perform required actions to avoid the threat (obstacle). After that drone should return to normal operation and continue according to its plan.

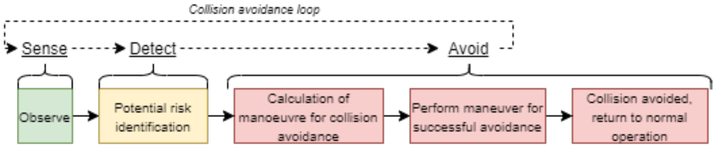


Figure 32: Structure of Collision avoidance system [14]

When it comes to decision making about what types of sensing equipment will be used for obstacle detection, individual assessment needs to be performed. On one side we have the dependence of passive sensors (video or IR cameras) on proper light conditions or quality of optical sensor, but they have low power consumption and do not require to install additional equipment (since IR and video cameras are already used as part of inspection equipment). Anyway, we will need additional sensors installed, because sensing cameras ae able to cover space only in front of the drones, not all 360°. On the other side - high precision of active sensors (e.g. LiDAR) with no limitations on weather but higher power consumption and increasing of drone's total weight which will lead to shorter flight time.

5.2.4 Positioning

Outdoor navigation

Since FPSO is always in motion and need of high precision of drones' attitude to match the characteristics of sensing equipment there is need to use some advanced navigation technologies. Relay on GPS only in not sufficient – tests shows that precision of positioning falls radically caused by interference between direct and reflected signals (so-called "multipath propagation") from present metal surfaces (vessel) [110]. Even we want to have the set up as simple as possible to get a highly efficient system on low costs, there is probability that there will be need to use several solutions for localization and navigation. Operating several types of drones above the Arctic Circle plays a significant role for set up of such systems.

Because of difference in operation of fixed-wing and multirotor, we can use different navigation detection approaches (Figure 33).

For the fixed-wing drones, which will be used mostly for search and rescue, we can use the standard GPS solution, since it will not be affected by distortion of operating near metals. To be able to safely land this type of drones on a helideck there is need to have an additional system, such as visual-based. Advantage of using of a visual approach for landing on a helideck is that it is initially made as a high-contrast object to support helicopter landing 24/7 in different environmental conditions. Using a good visible, contrast lighting makes it a natural reference point for landing of a fixed-wing drones at both day and night (Figures 34-a and 34-b). Position of the vessel in always known, so in cases when drone approaches the ship from a direction when helideck is closed behind other structures, it is possible to send the drone along circulating patter around the ship until helipad becomes visible.

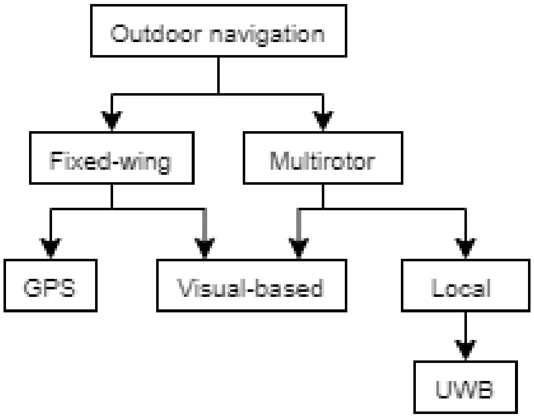


Figure 33: Proposed set up of outdoor navigation system

(a)

(b)

Figure 34: Helideck at different lighting conditions offshore: (a) night [15] (b) daylight [16]

Use of visual-based localization system for multirotors can be possible only during summer period or when lighting conditions are satisfied. One of the possible methods is to use image matching algorithm [111]. Once we have correctly extracted features (edges) and matched them to the reference images, we can calculate the absolute position of the UAV. Unfortunately, beside of the light dependence, reliability of that method depends on the distance from the object, because on short distances only few (if any) unique edges "image" can be captured. So, this method is more applicable for situations (use-cases), when drone flies on a curtain distance from the ship – overall monitoring, transportations, search, and others.

During arctic nights (or under any poor light conditions) visual-based solutions can have greatly reduced performance due to distortions and flairs cause by vessel's onboard illumination and low feature (edges) extraction due to not sufficient lighting. To be able to overcome these restrictions, as same as limitations of GPS, we need to use other methods. One of the possible solutions is to use LPS (Local Positioning System). This approach is based on a triangulation method and uses additional nodes (beacons or transmitters) installed on the vessel. This method provides precision on centimeter-level and does not interfere with conventional signals due to its pulse-based high bandwidth (bandwidth of 500MHz or higher than 20% of its center frequency [112]). Another positive side of a large bandwidth is its multipath resistance, what is highly relevant in our case [113]. To find a distance between UWB transmitter and desired object several methods being used: Time of arrival (TOA) and Time difference of arrival (TDOA) [114]. When using TOA, we calculate the distance d from each beacon (minimum four for 3D space) by formulas 2 (simplified) and 3 to find coordinates of an object in 3D space. Where c is speed of light, $t_{arrival} - r_{sent}$ is the time difference between signal has been sent from a node and arrived to the drone, $[x_{ref}, y_{ref}, z_{ref}]$ is the known position of one node.

$$d = c * (t_{arrival} - r_{sent}) \tag{2}$$

$$d = \sqrt{(x_{ref} - x)^2 + (y_{ref} - y)^2 + (z_{ref} - z)^2} \tag{3}$$

After we get the set of four equations of form of 3 for at least four nodes, we can find exact $[x, y, z]$ coordinates of a drone by calculating the intersection.

TDOA method is similar to TOA, but it based on a calculation of a distance by sending a signal *from* drone to a node. Signal sent from a drone being received by two nodes, and difference between arriving time at each node can be used to calculate the difference in distances (Δd) between drone and these nodes 4, Figure 35. Where $[x_1, y_1, z_1]$ and $[x_2, y_2, z_2]$ are coordinates of nodes 1 and respectively and $[x, y, z]$ are coordinates of a drone. After equations for all four nodes are found, it is possible to solve a system of equations to find the coordinates of a drone.

$$\Delta d = \sqrt{(x_2 - x)^2 - (y_2 - y)^2 - (z_2 - z)^2} - \sqrt{(x_1 - x)^2 - (y_1 - y)^2 - (z_1 - z)^2} \tag{4}$$

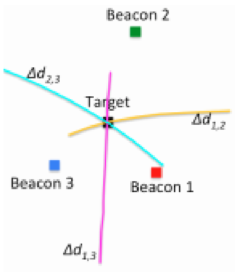


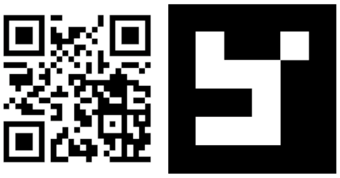
Figure 35: Visualization of TDOA method (2D space)

Due to dependency of a UWB method on a VLOS, it can be extended with Extended Kalman Filter to reduce localization estimation error when drone is out of line of sight of UWB beacons [113].

Indoor navigation

For navigation inside cargo holds and ballast tanks presents difficulties, because it is impossible to establish stable communication between drone and GPS or radio beacons installed on deck. So, here it is needed to use additional, most probable, visual-based solutions. According to performed research, there does not exist any solution to implement automated navigation inside ships. Metall surroundings can cause reflections and noise in signal of active sensors and lack of unique characteristics of the shell plating will make it difficult to use artificial inelegance.

To solve the problem, we can apply special markings along plating, which will help to identify position of the drone. They can be formed as a unique QR or ArUco markers (Figure 36), which can be easily interpreted by drone's visual system even in poor lighting conditions. It will give the possibility to calculate approximate position of the drone. TO improve results we can use stereo cameras, we can calculate distance and angle to these marks which will give precise location of the inspection drone [115]. It also can be possible to use the similar approach which would be used for navigation outside of the vessel – triangulation by UWB modules [116] located inside the tanks/holds. Unfortunately, having radio electronic components installed inside ATEX



(a) (b)

Figure 36: Example of QR code (a) and ArUco (b)

Zone-0 areas can be dangerous, so more research needs to be done in this field. One of the possible solutions is to use (switch on) these nodes during inspections only, when tanks are approved to be safe.

5.3 UAS - subsystems and supply infrastructure

Beside of the landing pads or catapults, there is need to have additional equipment on the vessel to ensure trouble-free operation of the drones. Basically, supply infrastructure can be divided into two parts: Remote navigation assistance and Computing task offloading (Figure 37) [117].

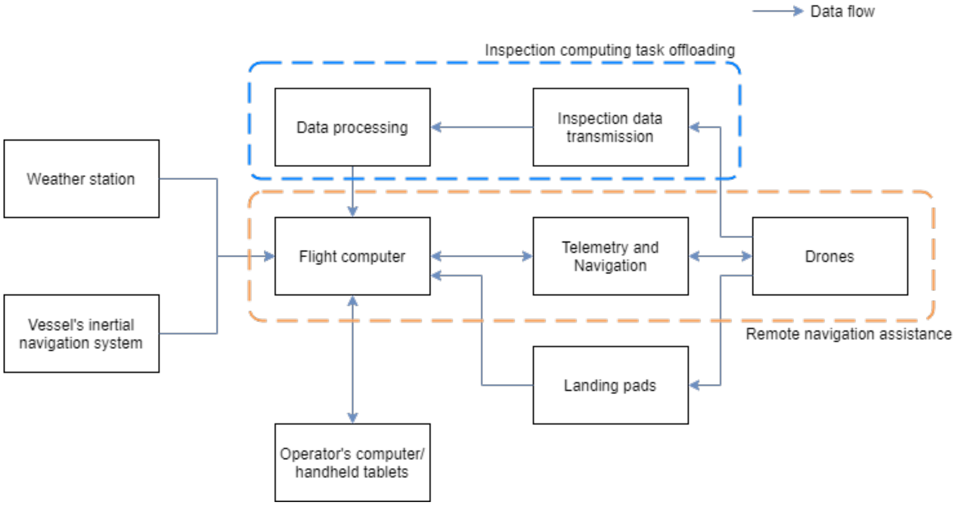


Figure 37: Supply infrastructure – communication architecture

Remote navigation assistance is responsible for everything related to the flight logistics' computations and control. It consists of flight computer and telecommunication unit for transmission of telemetry data. Telemetry contains information about drone's subsystems status, such as [118]:

- Voltage of the batteries
- Current consumption
- Battery temperature
- Flight controller operating mode
- Total flight time
- Altitude
- Linear velocity
- Inertial measurement data (from gyroscope and accelerometer)
- Motors' speed (rpm)
- Current position
- Status of sensing equipment
- Current mission progress

Based on this two-way communication computer can automatically steer drones and operator can keep control on progress of the mission and overall "health" status of the drones. To reduce power consumption and to minimize possible interference with other onboard radio equipment, telemetry data being send in packages in time intervals. Even flight control computer can provide fast rerouting to avoid collisions, it is preferable to have independent flight processor onboard the drone. It will ensure collision avoidance with minimized latencies, as same as accident-free flight on case of communication loss. For double redundancy entire path and algorithms for how to react in possible critical situations (e.g. communication loss or signal disturbances) must be uploaded and stored in drone's onboard memory.

"Computing task offloading" subsystem is responsible for all complex calculations that would overload the processing subsystems onboard the drone or take more time due to processing limitations. As example, it can be image or contact-sensor data processing during inspection. In this case it is better to transfer captured data to stationary computer and process it there to ensure fast computations. This subsystem consists of one-way telecommunication antennas which receives data from the drone, which being further passed to Data processing computer. Processed video data will be also used as visual odometry by Flight computer to correct the trajectory of the drone if needed.

6 Discussion

Even though drones have existed and being used for a long time by military and hobbyists, their civil use is relatively young and still rapidly growing. Being able to reach remote places without setting crew or survey team in danger, they are used for visual inspections in majority of industry sectors. During last few years interest to use UAVs in maritime has also raised. Despite of several challenges, their performance seems to be promising as innovative technologies being developed. The overall complexity of this project is that there does not exist any autonomous inspection or monitoring solution for maritime. There are only few projects that are related to use of aerial vehicles for maritime needs, as it was described in “Literature review” section, and all of them are still on development stage.

6.1 Technological and Regulatory gaps

There have been several times mentioned technological and regulatory gaps during project. Unfortunately, on present level of technology there is few possibilities to implement fully autonomous inspection system, especially for internal inspections. It is based not only on incompleteness of some technologies but also impossibilities due to technical structure of the ship itself. One of the examples is realization of automated fly in/out to ballast tanks and cargo holds – there is no possibility to get into these directly from the main deck, where all landing pads are planned to be installed. They are accessible only via manhole-sized hatches from inside of the vessel. Another problem is the navigation inside of those areas – getting high disturbances caused by multipath propagation makes it impossible to use radionavigation methods.

Use of aerial manipulators, especially if they will be used for NDT contact-based testing, requires additional research, what will allow us to use them in more complex weather conditions. Even, if there has already been used drones for onshore contact surveys, they are normally done under most optimal weather conditions. While operating offshore in most cases means flying in tough (i.e., inclement) weather.

Any professional drone operations need to be covered by laws and regulations, which binds different actors together, ensures order and uniform view on different things. Unfortunately, there does not exist any regulation that will cover the aspect of automated offshore drone operations. Those that exists are related to manual piloting with “one per time” intentions rather than continuous flights.

6.2 Use-case scenarios

In section 3 we have seen the proposed possible use-case scenarios. Based on present technological level of drone's development, implementation of complex missions, such as use of aerial manipulators for actual maintenance (i.e., repairing) is not possible. It is not only because of it will require use of much heavier multirotors, but they will have another requirement level for power supplement, so traditional batteries will not be sufficient, and need to be replaced by tethers. Which in turn will rise the difficulty of access to remote or clattered areas. Another limitation that comes with dimension increasement of drones (which is not related to tether) is that ships, particularly FPSOs, have quite compact arrangement, that will deny passage between construction elements or access through manhole-sized hatches of bigger drones. Additionally, all complicated repairing works of the hull or other constructions are meant to be done during drydocking. Thus, having complex and heavy drones that has limited field of application is not worth the costs, so it could better to concentrate on *finding* than *fixing*. That leads to those most common tasks will be visual-based and contact-based inspections. Visual inspections using video or IR cameras are quite simple and not costly, but at the same time are quite effective. Their main disadvantage is that they can suffer from both poor lighting and solar radiation (during daylight). To minimize the possibilities of misdetection, they will be supported by drones with contact-based sensing equipment. This kind of division by attached implements is done to reduce number of sophisticated drones, thus reduce costs. Another reason is that frequency of missions, where these manipulators or other special equipment will be used, is expected to be low. So, it is not worthen to carry all the time equipment that will not be used for most of the flight time. At the same time, having ability to inspect hard-to-reach places will significantly reduce load on inspection team and minimize risks for injury.

Reason for including of search-and-rescue use-cases is that FPSO will be located at a sufficient distance from the nearest rescue base, so in case of any emergency it can take up to eight hours before first help arrives. In these situations, drones can become handy, as they can be deployed in minutes.

6.3 Implementation sequence

Since it is not possible to implement fully autonomous UAV-based system right from the outset, we can try to propose possible sequence of implementation process. To achieve that we will be based on existing autonomy gradient (Tables 6 and 7). Main factor that can affect and make changes in it, is development speed of technologies and dedicated regulations. Given the fact that European Commission has initiated the launch of the similar project ("ROBINS"), it shows high necessity to fill existing gaps, we can expect movements in that direction in nearest future.

7 Conclusion and Future work

7.1 Conclusions

This study has been done in order to propose possible use-case scenarios and as an attempt to set up the general Concept and Framework in order to implement the fully autonomous UAV-based inspection setup that could be used on FPSO vessels, mainly on Johan Castberg. To do that there has been performed research of the key components that were seen as important or could make a significant impact on the general development and implementation. Because of there does not exist similar system, focus was on finding possible components and algorithms, and propose general flow of the potential arrangement.

Performed research shows that in spite of the existing regulatory and technological gaps, development and further implementation of such inspection system *is feasible*, with some restrictions:

1. Weather conditions in the Barents Sea periodically may not allow operation 24/7.
2. ATEX regulations put strong restrictions on the equipment, what reduce choice of approved equipment
3. Autonomous inspection of the cargo holds and ballast tanks cannot be performed by UAVs, if they will need to takeoff from the main deck.

If implementation will be performed in steps as it being proposed in Chapter 4.7 (i.e. from “simple” to “complex”) results that have been proposed in this project can be used as a base for further “Detailed Design and Analysis” stage. Otherwise, this work has to be extended to cover existing gaps first.

7.2 Future work

To define concept and framework of a such complex inspection system is quite challenging, what normally requires cooperation of people that have knowledge in various fields of science. Thus, this project can be seen as the basis for future development of that system. Before we get regulatory side in place, it is possible to focus on the technical aspects, both practical and theoretical.

7.2.1 Practical aspects

We relate practical aspects to the practical realization and use. Even though it can be seen as part of low-level design, it is important to have them in place to be able to extend the system's capabilities.

- To get proper possibilities to perform contact-based inspections, additional study on practical use of **aerial manipulators** and NDT testing needs to be done. It will also allow to expand the list of use-case scenarios, what will increase total effectiveness.
- Another important point is the **positioning and navigation in GPS-denied areas**, such cargo holds and ballast tanks.
- There is a need to **develop control strategies** for the drones, so that there will be possibility to perform contact-based inspections in rough weather.

7.2.2 Theoretical aspects

Outlining theoretical aspects is an important part of concept generation process. Understanding the requirements and correctly placed accents can significantly reduce probability of failure and increase total effectiveness of the system in the future.

- In this work, we have focused on use of the unmanned aerial vehicles (UAV) only. However, **opportunity to use unmanned underwater vehicles (UUV) and unmanned ground vehicles (UGV)** is of no less interest.
- There is a need to **perform a feasibility study for implementation of autonomous fly-in and fly-out into the FPSO's cargo holds and ballast tanks (or look for possibilities to use another types of unmanned vehicles)**, because existing regulations and technical limitations do not give any possibility for that today.

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Appendix A Regulation on aircraft without pilot onboard, selected paragraphs (original text in Norwegian)

§ 51. Sikkerhetsavstander, maksimal flygehøyde

All flyging må skje på en hensynsfull måte som ikke utsetter luftfartøy, personer, fugler, dyr eller eiendom for risiko for skade eller for øvrig er til sjenanse for allmennheten.

Luftfartøyet må til enhver tid være godt synlig for den som fører det. Ved enhver flyging skal det holdes nødvendige sikkerhetsavstander. Det er ikke tillatt å fly

(a) høyere enn 120 meter over bakken eller vannet

(b) nærmere enn 150 meter fra folkeansamling på mer enn 100 personer

(c) nærmere enn 50 meter fra personer, motorkjøretøy eller bygning som ikke er under pilotens og fartøysjefens kontroll.

Luftfartøy som har en MTOM på 250 gram eller mindre, kan flys VLOS, EVLOS eller BLOS, men ikke høyere enn 50 meter over bakken eller vannet. Sikkerhetsavstandene i andre ledd bokstav b og c gjelder ikke.

Flyging ut over det som følger av sikkerhetsavstandene i andre og tredje ledd, kan bare utføres av RO 3-operatør i tråd med bestemmelsene i kapittel 9 og for øvrig de vilkår som er gitt i tillatelsen.

§ 56. BLOS

Flyging BLOS er kun tillatt hvis tillatelsen fra Luftfartstilsynet omfatter denne operasjonstypen.

§ 57. BLOS-flyging opp til 120 meter i luftrom klasse G

BLOS-flyging opp til 120 meter i luftrom klasse G eller luftrom klasse G med etablert Radio Mandatory Zone (RMZ), kan kun skje hvis det er utstedt NOTAM for å informere om aktiviteten. NOTAM skal være utstedt minst 12 timer før aktiviteten påbegynnes.

BLOS-flyging i luftrom klasse G med etablert Radio Mandatory Zone (RMZ) kan i særlige tilfeller likevel skje etter tillatelse fra flygeinformasjonstjenesten og på de vilkår som flygeinformasjonstjenesten setter. Flygeinformasjonstjenesten kan kun gi tillatelse til slik flyging hvis det er klart at flygingen kan gjennomføres sikkert og uten å hindre øvrig lufttrafikk.

§ 58. BLOS-flyging opp til 120 meter i kontrollert luftrom

BLOS-flyging opp til 120 meter i kontrollert luftrom kan kun skje i aktive fare- eller restriksjonsområder.

BLOS-flyging kan unntaksvis skje utenfor fare- eller restriksjonsområde, etter klarering fra flygekontrolltjenesten og på de vilkår som flygekontrolltjenesten setter. Klarering skal kun gis hvis det kan etableres tilfredsstillende atskillelse mellom luftfartøyet som ikke har fører om bord og ethvert annet luftfartøy.

§ 59. Påbudt lys

For all flyging BLOS skal luftfartøyet være utrustet med lavintense lys, hvitt med minst 10 candela, hvor blink fremkalles ved roterende lys (strobelys) og med minimum 20 blink i minuttet.

§ 60. Flyging i mørke

Ved flyging i mørke skal luftfartøyet ha belysning i samsvar med kravene i forordning (EU) nr. 923/2012, SERA.3215, gjennomført ved forskrift 14. desember 2016 nr. 1578 om lufttrafikkregler og operative prosedyrer.