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Development and onboard assessment of drone for assistance in firefighting resource management and rescue operations

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Abstract

This report provides comprehensive information for deciding whether to pursue the deployment of a drone system for increasing safety on ship. The assessments of technical and legal feasibility as well as usefulness of a drone system for surveying the open decks of a ro-ro ship are presented. The use cases of fire patrol, fire resource management and search & rescue operations are targeted. A prototype drone system is detailed that is built on open standards and open-source software for high extensibility and reproducibility. Technical feasibility is assessed positively overall using a purpose-designed drone-control software, in-field tests and a demonstration onboard of DFDS Petunia Seaways. The needs for further development, analysis and long-term tests are described. The legal feasibility assessment gives an overview of applicable maritime and airspace regulations within the EU. It concludes that the drone system should be seen complementary to existing fire safety systems and that operational authorization is best applied for in collaboration with a ship owner. Usefulness is assessed using responses from maritime experts to an online questionnaire on the targeted use cases. Results are positive with two major challenges identified: achieving a reasonable selling price and obtaining the ship operators' and crews' trust in the system. Finally, a SWOT analysis gives a concise summary of the performed assessments and can be used as input to the strategic business planning for a potential drone system provider.

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Contents

1 Executive summary

Unmanned aerial vehicles (UAV), commonly referred to as *drones*, have entered mainstream markets and new applications are presented daily on the news. They are increasingly used in industrial applications with high demands for reliability and safety, e.g., aerial surveying, inspection, delivery or autonomous search and rescue operations.

The aim of the drone system that is investigated within LASH FIRE is to support the crew on a ship in fire prevention and firefighting. To this end, this report assesses the technical and legal feasibility, as well as the usefulness of such a system. The assessments are based on a prototype design of a drone system that is presented together with a cost estimate. Further input was gathered during simulations, in-field tests, a demonstration on board DFDS Petunia Seaways and using an online questionnaire that was sent to experts in the broad maritime field. In the LASH FIRE context, the drone system is a mobile sensor that feeds information into the Firefighting Resource Management Centre (FRMC) (more specifically the Digital Fire Central (DFC)), presented in D07.4.

The drone is intended to fly outside of the ship, i.e., it monitors the open decks. Three use cases are subject to our assessments: fire patrol, fire resource management as well as search and rescue missions. The use cases themselves and a common set of requirements to fulfil them are defined in this report. As the use cases have overlapping functionality, four *operational modes* (Fly to Coordinate, Hover, Global Mission, Relative Mission) are defined as underlying functional building blocks. We implemented each of these operational modes in our prototype drone control software called “Control Tower” in order to analyse them for technical feasibility. We further analyse potential interferences on the drone system’s sensors and draw conclusions about the technical feasibility of each of the defined requirements individually. Overall, we evaluate technical feasibility positively but show the need for further development (automated landing on a sailing vessel), analysis (electromagnetic compatibility) and long-term tests (weather resistance and overall reliability).

The assessment of legal feasibility gives an overview of applicable maritime and airspace regulations primary within the EU. It exposes a high degree of complexity in certifying an autonomous drone system that should be connected to a vessel’s fire safety system. We conclude that the drone system will be complementary, and that operational authorization should be applied for in tight cooperation with a ship owner as well as a ship classification society to move forward effectively.

The assessment of usefulness is based on results from an online questionnaire that was sent to LASH FIRE partners, the Swedish Maritime Administration and maritime experts within RISE (incl. SSPA Sweden). The questionnaire itself presented the drone system’s three use cases using video material gathered during the on-ship demonstration on DFDS Petunia Seaways. The experts’ opinions on the system's usefulness for each use case as well as aspects influencing it were surveyed. We discuss that the drone system is generally perceived as useful, and the market seems to be open for such a system on the weather deck according to the results. While all use cases are positively commented on in general, the search and rescue use case is seen as the most promising for the drone system to improve. However, two major challenges remain: achieving a reasonable selling price and obtaining the ship operators’ and crews’ trust in the system.

Finally, the results from feasibility and usefulness assessments are summarized in a strength, weaknesses, opportunities and threats (SWOT) analysis that can help potential providers of an on-board drone system in their strategic business planning.

In conclusion, this report provides the system design as well as technical, legal and usefulness assessments for a drone-based support system with a focus on preventing and detecting fires on ships. A secondary focus is supporting search and rescue missions. Using automation, we directly contribute to the LASH FIRE WP7 objectives of *accelerating time sensitive tasks* and *reducing the potential for human error*. In combination with the FRMC, we contribute to the objective of effective decision support by providing a thermal overview from a bird's-eye view. As the chosen technologies are to a large extent based on open standards as well as open-source hardware and software, the presented system is reproducible by others. We further release our implementation of a drone control application prototype for the targeted use cases as open-source software[1]. In sum, we foster technological means for enhancing fire prevention on ro-ro ships.

[1] https://github.com/RISE-Dependable-Transport-Systems/ControlTower

2 List of symbols and abbreviations

CCTV	Closed-Circuit Television
DFC	Digital Fire Central
EASA	European Union Aviation Safety Agency
FRMC	Firefighting Resource Management Centre
FSS	Fire Safety System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMO	International Maritime Organization
IMU	Inertial Measurement Unit
MAV	Micro Air Vehicle
MED	Marine Equipment Directive
NAA	National Aviation Authority
PDRA	Pre-Defined Risk Assessment
ROI	Region of Interest
RTK	Real-Time Kinematic
SDK	Software Development Kit
SOLAS	Safety of Life at Sea
SORA	Specific Operation Risk Assessment
STS	Standard Scenario
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle

3 Introduction

Unmanned aerial vehicles (UAV), also called *drones* as in the remainder of this text, have entered mainstream markets and new applications are presented daily on the news. Since their description by Nicola Tesla in 1915, drones have been a source of challenging research questions, e.g., in control theory, position estimation, route planning, communication technology and many more [1]. While drones originally became infamously known in mainstream media for their use in military applications, their perceived value for emerging civil applications hardly knows any boundaries today. Apart from entertainment purposes like drone racing, cinematography, or live broadcasting, drones are increasingly used in industrial applications with high demands for reliability and safety, e.g., aerial surveying, inspection, delivery or autonomous search and rescue operations. Figure 1 shows the *multicopters*, i.e., a specific kind of drone detailed in Section 6.2.1, as used within LASH FIRE.

Figure 1 Example of drones used for the developments within LASH FIRE

This report presents an attempt to support a ship's crew in fire prevention and firefighting. To achieve this, a drone system is prototyped and analysed for feasibility and usefulness. In the envisioned use cases, the drone takes off periodically from an open deck for autonomous gathering and processing of sensor data. Take-off can be triggered automatically by an event (e.g., fire alarm) or manually by the crew. In case of a periodic launch, the drone flies a pre-defined path to get a general overview of the ship and check whether a temperature rise can be detected. If so, the crew will be notified. In case of a manual launch, an interface is presented to the crew that enables moving the drone to a certain point on the ship to get detailed information, e.g., a thermal image of a specific area.

Deploying a drone onboard of a ship provides unique challenges. An obvious challenge is the adverse weather conditions that need to be considered when choosing the type of drone and designing the system. Further, it is important to design a user-friendly system. It must be assumed that when using it the crew works in a very stressful situation and can be occupied with other urgent tasks. Therefore, the resources to control and evaluate drone operations might be very limited, and the benefits of deploying the drone need to be convincing and achieved with as little interference of the crew as possible to get it accepted.

Within LASH FIRE a special focus is on how drones can be used for fire patrol and fire resource management, but also for search and rescue missions. These three use cases are detailed in Chapter 4, including the requirements on the system that these use cases pose. In the remainder of this chapter, we provide a brief overview of related EU-funded projects and summarize the structure of this report.

3.1 Related Work

There are several related projects financed by the European Commission through the Horizon programmes that are either about drones or contain drone-related research in some way. In the following, a non-exhaustive list of major projects with a drone focus is presented:

- **Drones4Safety** (https://drones4safety.eu/)
  Drones4Safety (D4S) aims to develop a system of autonomous, self-charging, and collaborative drones that can inspect a big portion of transportation infrastructures in a continuous operation.
  Objectives of the project are:

1.	*Energy Harvesting:*	Harvesting energy from overhead power or rail lines in the proximity of the infrastructure to be inspected to operate the drones for a longer time.
2.	*Inspection efficiency:*	Improving an AI algorithms to recognize infrastructure components and discover automatically eventual faults on assets.
3.	*Failsafe Inspection:*	Producing a safe operational system resisting harsh electromagnetic environments and the effects of high-voltage/high-current signals.
4.	*Collaborative system:*	Validating a collaborative and centralized drone system to inspect different sides of the desired infrastructure.
5.	*Autonomous Navigation:*	Providing a drone system monitoring and controlling remotely the state and location of the drone.

  Objective (1) is interesting but probably not relevant for ships in a short time. Objective (2) is relevant, but on a more general project level than drone development. Objective (3) is probably relevant considering the environment on a ship with, e.g., RADARs emitting electromagnetic radiation. Objective (4) is not relevant in the first phase but may be relevant in future for considering operating several drones on one ship or in an operation with drones from more than one ship. Objective (5) is quite fundamental for autonomous drone operation in general and, thus, relevant. In summary, some inspiration can be drawn from Drones4Safety, but the objectives have quite a different focus.
- **5G!Drones** (https://5gdrones.eu/)
  5G!Drones aim to trial for drone use-cases: UC1 UAV Traffic Management (UTM), UC2 Public safety/saving lives, UC3 Situation awareness, and UC4 Connectivity during crowded events. These four use cases shall cover the trial of the 5G services eMBB[2], URLLC[3], and mMTC[4], and validate 5G KPIs for supporting such challenging use-cases.
  5G technology is out of scope for LASH FIRE, but the use cases are relevant. UTM may be necessary to operate the drones when a ship is close to land and connectivity during crowded events may also be an issue. Public safety/saving lives and situation awareness related to fire detection and man overboard use cases on a ship. The project, however, is very much focused on evaluations and 5G technology itself which provides less input for our work and more input for the question of deploying a 5G network on a ship.
- **AW Drones** (https://www.aw-drones.eu/)
  AW Drones focus is on supporting the implementation of coherent and interoperable global

[2] enhanced Mobile Broadband
[3] Ultra Reliable Low Latency Communications
[4] massive Machine Type Communications

standards for drones in the EU and providing guidance for the harmonisation of standards to support future drone regulation.

- **COMP4DRONES** (https://www.comp4drones.eu/)
  COMP4DRONES is an ECSEL JU project with the aim of providing a framework of key enabling technologies for safe and autonomous drones. Focus objectives are:
  1. Ease **the integration and customization** of embedded drone systems.
  2. Enable drones to take **safe autonomous decisions**.
  3. Ensure the deployment of **trusted communications**.
  4. Minimize the **design and verification effort** for complex drone applications.
  5. Ensuring **sustainable impact** and the creation of an industry-driven community.

  Use cases in focus are

Transport	Drones for optimization of transport control, operation and infrastructure management.
Construction	Drones for virtual design, construction and operation of transport infrastructures.
Logistics	Logistic using heterogeneous drone fleet.
Surveillance and Inspection	Drone and wheeled robotic systems for inspection, surveillance and rescue operations.
Agriculture	Smart and Precision Agriculture: From drone to rover.

  The project published several relevant deliverables on drone system design that provide extensive background information to our work. Their “Transport” use case aims for a demonstrator for a drone supporting port operations. This is a complementary use case to the use cases presented in this report but no public documentation is available yet.
- **RAPID** (https://rapid2020.eu)
  Risk-aware Automated Port Inspection Drones (RAPID) targets “fully automated and safety-assured maintenance inspection service for bridges, ship hull surveys, and more. Specifically, the service will combine self-sailing unmanned surface vehicles with autonomous unmanned aerial systems.” Due to the project’s focus on ports, the use cases and challenges are naturally related to the use cases presented in this work. Especially deliverables on feasible market opportunities and regulatory compliance can be interesting when trying to expand the use cases provided using the drone system presented in this work. Most of the deliverables are yet to be published at the time of writing. In contrast to our on-ship context, however, the surface vehicle and aerial system seem to launch from the shore and, thus, have a fixed base which can fundamentally change the system design as detailed in the following chapters.

In summary, several related research projects exist internationally but none of those target the use case of a drone on a sailing ship and the unique challenges it provides. Apart from research projects, numerous start-ups exist that are working on drone-based services for all kinds of use cases. A notable mention is the Danish start-up Upteko [2] which is focusing on the maritime sector. Upteko is cooperating with the Danish shipping company DFDS on testing a drone system for supporting the captain in docking and sailing in narrow waters[5]. In the early stages of LASH FIRE, we had several technical discussions with Upteko.

[5] https://www.dfds.com/en/about/media/news/first-in-the-world-dfds-introduces-eyes-in-the-sky

3.2 Structure of this Document

In the following chapter, the targeted use cases for a drone on ship are detailed including high-level requirements for the drone system. Chapter 5 presents the high-level architecture of the drone system that we designed for the use cases, specifically. The hardware and software design of the drone system is detailed in Chapter 6 including a cost estimate. The drone system design was further implemented and forms the basis for analyses performed in the following chapters. Chapter 7 presents the demonstration and validation setup that was used for collecting data and experience with the implemented drone system on land and ship. The data and experience gathered are used for analysing the technical and legal feasibility of the use of a drone for the targeted use cases in Chapter 8. Chapter 9 describes the results from an online questionnaire that we specifically designed to assess the usefulness of the drone system according to industry experts. Discussions from all previous chapters are summarized in a strength, weaknesses, opportunities and threats (SWOT) analysis in Chapter 10. Finally, our conclusions follow in the last chapter.

4 Use Cases of a Drone on Ship

As mentioned in the introduction and in line with the LASH FIRE project in general, the work on the drone system focuses on fire safety challenges. Special focus is on reducing delays in fire detection and alert, as well as improving fire resource management by providing a detailed overview of a fire incident. This is addressed in the two use cases of fire patrols and fire resource management detailed below. Additionally, a third use case of search and rescue missions is presented, which seems suitable for the same technology that is required in the first two use cases. Search and rescue missions were, however, not the main focus during the design of the drone system.

In general, it needs to be noted that crew acceptance is critical. While technological advances provide a lot of room for creativity for functionalities that the drone system can provide, e.g., tight collaboration with the crew on deck, these functionalities require specific education in using the drone and will mean additional responsibilities for the crew. This can be problematic because the crew's time is already a constrained resource in the use cases presented below. A lot of information needs to be acted upon under time pressure, especially in critical situations like a fire incident. Eventually, this could mean that the crew would not accept nor use the system (see Chapter 9 for the assessment of usefulness based on an online questionnaire). Therefore, our focus is to explore the benefit of a drone system on the weather deck with as little intervention required by the crew as possible. At the same time, the system needs to be reliable as, again, acceptance depends on it. In summary, the goal is to provide clear benefits in timely fire detection and fire incident overview using an autonomous and robust drone system.

4.1 Use Case 1: Fire Patrol

The main use case is to detect fires or critical temperatures using automated fire patrols. Fire patrols, also called fire rounds, are usually carried out by the crew, where one or more crew members walk a predefined route at certain intervals with the aim of detecting potential fires promptly. According to Safety of Life at Sea (SOLAS) Chapter II-2 Regulation 7.8.1 [3], fire rounds need to be carried out on ships carrying more than 36 passengers by personnel "familiar with the arrangements of the ship as well as the location and operation of any equipment he may be called upon to use".

This use case has great potential for automation: the predefined route can be covered by an autonomous drone with the same or even shorter time intervals. A human performing the fire patrol performs a visual inspection combined with using their nose to sense the smell of smoke. The idea in LASH FIRE is to instead use a thermal camera-equipped drone and identify fires and critical temperatures by analysing recorded visible and thermal images and videos. Using state-of-the-art thermal cameras is expected to be superior in detecting critical temperatures, and consequently potential fires, in terms of area covered and accuracy on the weather deck. At the same time, in case the drone might not be available[6], e.g., due to technical errors or severe weather, the fallback of a manual fire patrol performed by the crew would still be available.

In summary, the use case of fire patrols is suitable as an early use case that promises benefits for the crew in terms of time savings and even increased safety when shorter intervals are applied and the time the crew needs to walk along the weather deck is reduced.

[6] Weather resistance requirements are discussed in the following sections.

4.2 Use Case 2: Fire Resource Management

In case of an active fire, allocation of resources is critical to achieve as efficient containment of the fire as possible while maintaining general safety as well as potentially performing and managing evacuation. At the same time, it is challenging to get and maintain an overview of the situation.

While video surveillance (also called closed-circuit television, CCTV) in the form of fixed thermal and visible imaging cameras virtually covers the whole weather deck on modern ships, the aerial perspective provided by a drone-mounted thermal camera can provide an overview of critical situations and bigger areas. This can save time in the verification of a fire indicated by ship-mounted camera, and also detect fires located in directions where the fixed video surveillance field of view is blocked, e.g., by cargo.

Availability limitations of the drone system, e.g., due to technical limitations like empty batteries or in severe weather, raise questions like to what extend the crew can rely on the system for this use case. Downtimes for charging an empty battery can be expected to be about 20 to 30 minutes, which then allows similar flight times. Downtimes can be reduced considerably by either employing two drones (one in operation while the other is charging) or swapping instead of charging the batteries (which either requires crew intervention or a more complicated automated charging system). Weather tolerance requirements are further discussed below. Severe weather will degrade the functionality, e.g., such that the drone can still lift and scan the ship by tilting the thermal camera but only stay on a fixed position on the ship. It is, however, conceivable that there will be situations where the drone is unavailable. How reliable the system is and to what extent the crew can rely on it is a critical question that needs to be further discussed in the context of on-board assessments.

4.3 Use Case 3: Search and Rescue Missions

Man overboard incidents happen regularly and, at the same time, search and rescue missions are in the majority of cases unsuccessful. Data from cruise ships suggest that one or two people go overboard every month and 17% to 25% of them are successfully recovered [4]. The main problem is the time it takes to initiate the search and rescue mission: An average person will become unconscious in 5 °C cold water in under 15 minutes. This duration, however, is generally required to perform the most common manoeuvres to turn the ship back towards the point where the person is suspected to have gone overboard [5]. Within this time, the water current could already have moved the missing person considerably away from the moving ship.

Using the drone system to support search and rescue missions seems natural. The drone can rapidly move to the point where the person is suspected to have gone overboard and search the area with the thermal camera. With information from the ship's Automatic Identification System (AIS), ocean current estimates and the ship's movements can be considered. This can considerably speed up the search for the missing person and enable a timelier launch of a rescue boat.

This use case is not the focus of this report and will only be explored to a limited extend. More advanced functionality like dropping a life vest or other floatation device from the drone will only be sketched and are generally out of scope.

4.4 Requirements

Based on the use cases described in the previous sections, several high-level system requirements are defined as listed in Table 1.

Table 1 High-level system requirements identified for the drone system

Req	Description
R1	The drone needs to be able to position itself precisely.
R2	The drone needs to be able to follow predefined paths.
R3	The drone needs to be able to follow the ship's movements (positions and paths relative to the moving ship need to be supported).
R4	The drone needs to be able to record and stream high-quality colour and thermal images and videos.
R5	The drone needs to be able to communicate with the ship with long range (at least 1 km), high bandwidth (for live images) and relatively low latency to support relative positioning to the ship as well as timely notification of alarms.
R6	The drone needs to be able to maintain high availability, even during severe weather.
R7	The drone needs to be able to provide a high degree of automation and expect input from the crew only when desired by them. This includes especially automated take-off and landing.
R8	There should be limited maintenance needs either in big time intervals only such that it can be performed when docked, or feasible with a limited amount of training.
R9	The system should be useable by non-experts and require limited training only.

Severe, or harsh, weather is not well defined. However, some target numbers are needed and based on LASH FIRE internal discussions, i.e., we target tolerating weather conditions of 6 to 7 Beaufort as well as moderate to heavy rain. In numbers, Table 2 presents our targets. "Fully Operatable" means that the functions of the drone system are not limited in any way. "Absolute Maximum" means that in worst-case conditions like the ship going at 22 knots (top speed of ships like the M/S Stena Scandinavica) against 27 knots headwind the drone's movement would be limited: the drone would still be able to take off, hover at a fixed position relative to the ship and give an overview of the ship by moving the camera (but not itself). Further extending the specified limits is possible with financial investments that exceed the budget available. This is further discussed in Section 6.5.

Table 2 Target weather conditions for the drone system

	Absolute Min.	Fully Operatable	Absolute Max.	Unit
Temperature	-15		50	°C
True wind speed		> 22	27	knots
Wind gusts			33	knots
Max rain		> 7.6	10	mm/h
			30	mm/3h

The requirements presented in this section were further detailed in IR7.10 and are not repeated here. The presented detail is sufficient to understand the following chapters, especially, the feasibility analysis that is presented in Chapter 8. The feasibility analysis reviews the requirements presented here, but before, the following chapters present the drone system design that aims to fulfil the requirements.

5 High-Level System Architecture

This chapter describes the drone system architecture targeting the use cases presented in the previous chapter. The system consists of the drone itself, a computing system on board the ship and the communication between them. Alternatives to the different design choices made were evaluated but are not detailed here. In the following, only the assessed architecture design is presented.

A high-level illustration is shown in Figure 2. The drone carries a sensor payload in the form of a combined visual and thermal camera. It determines its global position using Global Navigation Satellite System (GNSS), i.e., satellite-based localisation. It receives control input from the computing system on board, which is called the *ground station*. Further, the drone sends its status, e.g., its position, velocity and battery state, as well as a live video and thermal data stream to the ground station.

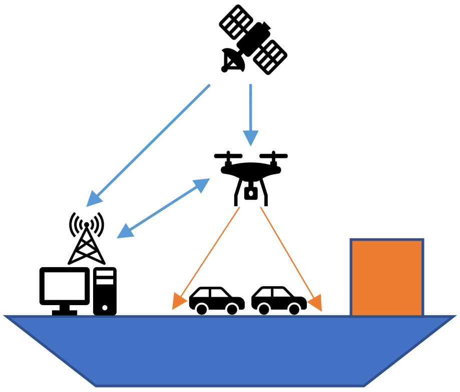

Figure 2 Conceptual illustration of the solution

The ground station provides the interface between drone and ship. It further provides the interfaces to other systems on ship and to the crew, i.e., users of the drone system, through the FRMC (presented in D07.4). All processing of video and thermal data as well as planning of movements of the drone are performed within the ground station. This results in less computing power demands on the drone and thus less power consumption and longer flight times. However, this also requires a constant, reliable communication between drone and ground station. Considering that the drone constantly needs to be informed about the movements of the ship to follow it, this kind of communication link is anyways required.

Figure 3 DFDS Petunia Seaways' monkey island can provide room for a drone docking station

5.1 Drone Storage Location and Automated Charging

Turnkey solutions exist to automatically store and charge the drone in a weatherproof case after landing, e.g., from Skycharge[7] or Hextronics[8]. Therefore, and because these systems cost several 10.000€ depending on the IP rating and certification required, automated charging was considered out of scope for the LASH FIRE project. Essentially, such a so-called *drone docking station* can be considered as a box that opens automatically when the drone approaches for landing, closes when landing is finished and either begins charging the batteries inside the drone or swaps them with charged ones. It could be mounted on or close to the *monkey island*, i.e., the deck directly located above the navigation bridge. An example of a monkey island is shown in Figure 3. Drone docking stations can even support the automated landing process as detailed in Section 8.1.4 as part of the feasibility analysis.

5.2 Drone System Operational Features

To fulfil the targeted use cases, four main operational modes are needed. The modes listed below are implemented by the prototype design that is detailed in the next chapter.

- **Fly to Coordinate:**
  A manual operator commands the drone to fly to a particular global coordinate by selecting the position on a map that is displayed on a screen. Independent from the drone's movements, the camera can be pointed to a region of interest (ROI). This mode of operation allows getting an overview of situations on the ship semi-manually, as the system supports the manual requests, e.g., controlling the drone's altitude.
  Relevant for use case: Search & Rescue, all when the ship is docked
- **Hover:**
  This is an extension to the "fly to coordinates" mode, where the operator commands the drone to keep its position relative to the ship's position. The drone will follow the ship's movements.
  Relevant for use case: Fire Patrol, Fire Resource Management
- **Global Mission:**
  A list of global coordinates is provided for the drone to visit. At each coordinate, a command can be executed like pointing the camera to a new ROI or taking a thermal or visual image. The list of coordinates and commands constitutes a *mission*, which is either pre-planned or generated, e.g., to search a certain sea area for a missing person.
  Relevant for use case: Search & Rescue, all when the ship is docked
- **Relative Mission:**
  An extension of the "mission" mode that requires the mission to move with the ship, i.e., coordinates are positions on the ship. We call this extension *relative mission* mode. The drone takes off automatically either at fixed intervals or when triggered by an event or manual operator and follows the relative mission.
  Relevant for use case: Fire Patrol, Fire Resource Management

Note that the drone can be localized and positioned in global coordinates and local coordinates (that represent positions on ship, see also R3 in Table 1). Inspection or surveillance of the ship is performed in coordinates relative to the ship (hover and relative mission modes), while man-overboard operations need to use absolute coordinates (fly to coordinate and global mission modes), e.g., to be able to include information about ocean currents into calculations. Independent from the

[7] https://www.skycharge.de
[8] https://www.hextronics.tech

chosen mode, the video from the camera can be processed in the ground station. In case something of interest is detected, like an unusually high temperature, a notification is sent to raise the attention of a manual operator.

6 Hardware and Software Design of the Drone System

This chapter describes the hardware and software design of the drone system prototype that was designed and evaluated during this project. Besides realizing the use cases described in Chapter 4, our goal was to present a flexible design that can be reproduced, adapted and fully analysed. We achieved this by basing our design on open standards for hardware and communications, as well as open-source software. Central to our design are projects from the *Dronecode Foundation* [6] for the design of micro air vehicles (MAV): *MAVLink (communication protocol)*, *PX4 (flight controller software)*, *MAVSDK (software development kit (SDK) for MAVLink-controlled vehicles)* and *QGroundControl (ground station software).* The projects are detailed in Sections 6.2.3 and 6.3. Dronecode is a vendor-neutral non-profit foundation under the Linux Foundation. It provides open-source hardware, software and open standards for drone projects. Projects based on Dronecode generally do not need to be released as open source. We do, however, release our prototype ground station software *Control Tower* (see Section 6.3.2) as an open-source project, such that the design presented below is fully reproducible and modifiable.

6.1 Scope and Limitations

The aim of the drone system prototype is the assessment of the feasibility and usefulness of a drone on the weather deck, specifically for the use cases described in Chapter 4. The developed drone system reached TRL6 (technology demonstrated in relevant environment) and the results of the assessments are detailed in the following chapters. During the assessments and the design of the prototype, limitations were identified that require further development to achieve TRL7 and higher. The limitations concern demonstration and validation, as well as functionality.

Demonstration and validation of the drone system were limited due to the COVID-19 pandemic, which made it first possible for us to perform on-ship tests in the summer of 2022, i.e., 5 months before this report was due. Effectively, we were only able to evaluate the system on a docked vessel.

Functionalities identified that are either incomplete or missing are the following (status within our prototype and use case mentioned in brackets):

- **Automated landing on moving ship** (partly implemented in simulation, all use cases). A solution called “Precision Landing” is implemented in PX4 but did not fulfil our requirements (see Section 8.1.4). Drone docking stations that integrate technology to assist the drone’s landing exist on the market, e.g., Skycharge Skyport DP5[9]. Internest LOLAS[10] is a standalone solution with additional sensors that is advertised specifically for moving vessels (among other application areas). Several visual solutions that use the camera image have been described in literature [7] [8]. They are often based on AprilTag [9].
- **Search path generation for drone to fly in case of missing person** (missing, search & rescue). Solutions have been presented in literature for drones, specifically [10]. Some take geographic information like surface currents into account [11].
- **People detection in water** (missing, search & rescue). Solutions that detect on thermal and/or visual images have been presented in literature [11].
- **Fire, smoke and high-temperature detection** (mostly missing, fire patrol). High-temperature detection based on temperature thresholds is available on the FLIR Duo Pro R camera that we used, but it is unclear whether it can be calibrated for the changing environmental circumstances on ship. Fire and smoke detection software that works on video streams exists

[9] https://www.skycharge.de/drone-box-hangar
[10] https://internest.fr/

on the market from a number of suppliers. Further solutions that work on visual and thermal have been presented in literature [12].

For all of the identified incomplete or missing functionalities, solutions exist that are either market ready or described in literature. Therefore, they do not limit our feasibility or usefulness analysis. In the following, the implemented drone system prototype design is described.

6.2 Hardware Design

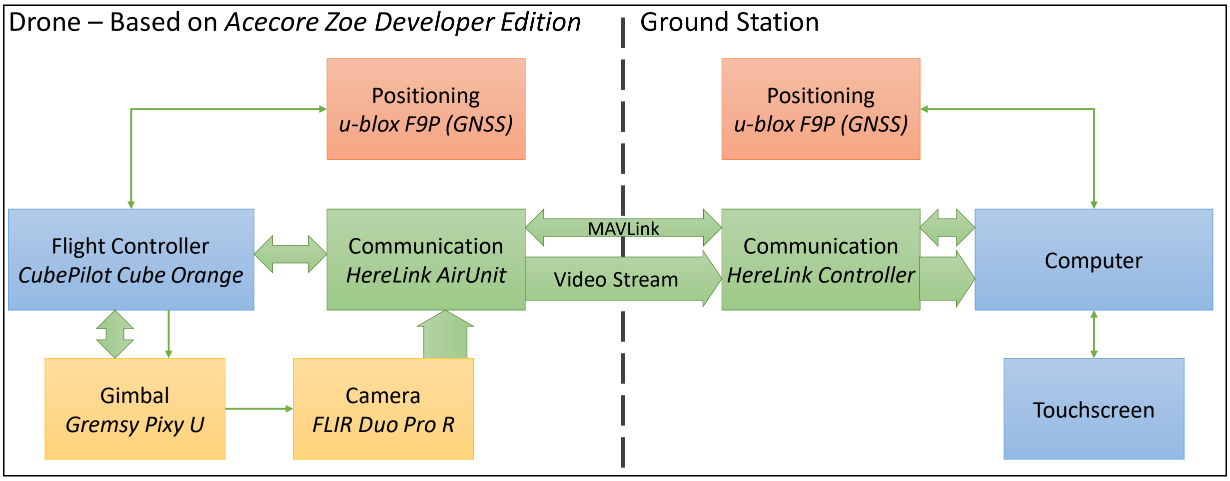

Figure 4 Hardware overview of the drone system (excluding motors and power distribution) detailed in this chapter

The hardware design of the ground station is, apart from a standard computer, defined by the hardware design of the drone. Therefore, a drone-centric view of the hardware design is presented. A high-level overview is given in Figure 4, the shown blocks are detailed in the following.

6.2.1 Drone Kit

The air vehicle design chosen for this project is a multicopter, i.e., an air vehicle type with more than two rotors on independent motors that cancel out their individual torque. Compared to other air vehicle designs, multicopters are relatively simple, they do not require a runway to lift or land, can tolerate strong winds and hover at a fixed position in the air [13]. The most common multicopter design is a *quadrocopter*, i.e., a multicopter with four rotors as shown in Figure 5. Quadrocopters were shown to be able to land safely even under motor failures[11].

[11] https://www.aopa.org/news-and-media/all-news/2019/april/26/this-failsafe-can-save-the-day-if-your-drone-loses-a-motor

Figure 5 Acecore Zoe, the quadrocopter used as a basis for the presented drone system

It is today neither economical nor effective to build a drone system from scratch. Instead, commercial *drone kits* provide a basis for adaptation and extension for specific use cases. There exist numerous drone kits for *quadrocopters* on the market in all shapes and sizes. For the LASH FIRE use cases, the *Zoe* development kit from Acecore Technologies was chosen [14], because it remained within the budget and fulfils the target weather conditions listed in Section 4.4. It is shown in Figure 5. The Zoe has a maximum flight time of around 40 minutes (depending on battery setup and payload) and a payload of up to 5 kg. It has an empty weight of just above 4 kg, an operating temperature range of -15°C to +50°C, handles wind speeds up to 27 knots with wind gusts up to 33 knots, and rain conditions of up to 10mm/h or 30 mm/3h. It has a top speed of 91 km/h (approx. 49 knots), which is just above a conceivable worst case of the ship going at top speed (22 knots, like the ro-ro ships Stena Scandinavica or DFDS Petunia Seaways) against the worst-case wind conditions specified in Section 4.4 (27 knots). This means, in case these worst-case conditions apply, the drone would still be able to take off, hover at a fixed position relative to the ship and give an overview of the ship by moving the camera (but not itself).

6.2.2 Flight Controller

Apart from the mechanical parts, a *flight controller* is required. The flight controller is a piece of hardware with a set of sensors and control outputs that allow an estimate of the drone’s movements and achieve a stable flight by controlling the speed of the drone’s motors. Modern flight controllers contain redundant sensors (Inertial Measurement Unit (IMUs) and barometers), numerous interfaces for extensions (Serial, USB, CAN) and enough processing power to not only support remote control input but also autopilot implementations.

Pixhawk is a set of open standards for designing flight controller hardware [15] and the dominant standard among off-the-shelf flight controllers. For our prototype, the “Cube Orange” from CubePilot is used [16]. It is based on the Pixhawk FMUv3 open hardware design[12]. We further tested the “Pixhawk 4” from Holybro which is based on the Pixhawk FMUv5 design and, essentially, any flight controller following Pixhawk FMUv3 or higher can support the targeted use cases presented in this report.

[12] To be precise, the Cube Orange deviates slightly from the Pixhawk standard by using patented connectors.

As mentioned in the previous chapter, all processing of video and thermal data as well as planning of movements is performed within the ground station. Therefore, no *companion computer*, e.g., like a Raspberry Pi, is needed to complement the flight controller on the drone.

6.2.3 Communication

An essential part of the drone system is the communication between the ground station and the drone. It is challenging because high bandwidth (video stream), range (several hundred meters, more for search & rescue), as well as reliability (control input), are needed. Furthermore, electromagnetic compatibility (EMC) with other technology on the ship needs to be ensured, especially the X- and S-band radar. Finally, regulatory requirements need to be met.

A discussion of different communication technology options was given in IR7.10. Our drone system prototype uses "HereLink" from CubePilot [17]. The HereLink system comprises an "Airunit" that is connected to the flight controller, and a handheld controller that communicates with the Airunit (see Figure 6). Similar to WLAN, the two units set up a radio link in the 2.4 GHz ISM band (industrial, scientific and medical) but use a proprietary protocol. The transmission range is advertised to be up to 20km. Video live stream (up to 1080p, 60Hz) as well as *MAVLink* messages are transmitted using the same link. MAVLink is the dominant communication protocol to interact with drones, e.g., controlling movements or receiving the current position. The handheld controller functions as the interface allowing the ground station to communicate with the drone and can even provide manual control input using joysticks. The manual control input overrides any current movements or autonomous functions of the drone and is used as a safety fallback.

Figure 6 HereLink system from CubePilot. Controller shown on the left, Airunit to be mounted on the drone on the right. Image taken from https://docs.cubepilot.org

6.2.4 Positioning & Orientation

When it comes to determining and controlling the drone's position and orientation, the main challenge is the fact that the reference point (the ship) is moving within the main use cases (fire patrol and fire resource management, see Chapter 4). This requires constant tracking of the ship's movements and moving the drone accordingly, even if the drone is hovering at a fixed position as seen from the ship. We chose a multiband GNSS receiver (satellite-based positioning), more specifically the "F9P" from u-blox [18], on the ship (ground station) and the drone. Combined with a magnetometer, it performs well for positioning as well as orientation and provides good precision. Such a combined GNSS receiver, antenna and magnetometer as shown in Figure 7 complements the sensors (IMU and magnetometer) integrated into the flight controller.

Figure 7 Holybro RTK GNSS receiver "H-RTK F9P Rover Lite" that combines GNSS receiver, antenna and magnetometer. Image taken from Holybro.com

For automated landing procedures, centimetre precision and very low latency is desired, especially when landing in a drone docking station with automated charging (see Section 5.1). We performed initial tests with Real-Time Kinematic GNSS (RTK GNSS) in *moving base* mode. In broad terms, RTK GNSS is a technique where the GNSS receiver receives external information from a GNSS base station to correct its position estimate [19]. With RTK GNSS, positioning can achieve centimetre precision. Moving base is a mode of RTK GNSS that is supported by some RTK GNSS receivers like the u-blox F9P mentioned earlier. It allows the GNSS base station to be moving instead of having a fixed and calibrated position on earth. Thus, the GNSS base station can be integrated into the ground station and move with the ship. The positive aspects of such an approach are that it is supported by the chosen GNSS receiver out of the box and no additional infrastructure is required on the ship. The negative aspect is that a high bandwidth and low latency communication between the GNSS receivers needs to be maintained at all times (details in Section 8.1.4). While the occasional loss of messages can be tolerated within the rest of the drone system (MAVLink messages and video stream), this is not the case for RTK GNSS as it can cause the position estimate to jump a few meters. Our experiments showed that most jumps can be corrected within a few hundred milliseconds, and results were overall promising, but we cannot give a recommendation for or against moving base RTK GNSS at this point. Further experiments on (a moving) ship are required.

An alternative to moving base RTK GNSS is supporting landing procedures using the drone docking station. Either, in combination with the drone-mounted camera (described in the next section) or an additional IR receiver on the drone. In this case, a visual landing target is marked on the docking station, e.g., using AprilTag [9], or by emitting an IR light pattern. Either way, the drone would use GNSS positioning (without RTK) to get close to the drone docking station and then the landing procedure would be supported with an additional positioning source.

While automated landing with a moving target was investigated to some extent in simulation and on land, further work is required for a full implementation on a moving ship.

6.2.5 Camera & Gimbal

While a broad range of sensors can be mounted on a drone, the most suitable for the use cases of this project were determined to be a visual and thermal camera. The visual image can be quickly interpreted by a human operator and is suitable for the automatic detection of smoke and fire. The thermal image complements the visual image by enabling the automatic detection of unusually high or developing heat as well as supporting the search & rescue case by enabling the detection of temperature differences in the water.

For our prototype, we use the “Duo Pro R High-Resolution Thermal and Visible-Light Imager” from FLIR. It is a combined thermal and visual camera that was specifically designed for drone integration. The FLIR Duo Pro R has a high-resolution thermal imager of 640x480 pixels, as well as a 4K visual image sensor [20]. The thermal imager’s spectral range is 7.5-13.5 µm, which makes it a longwave camera, and suitable for fire detection. The thermal sensitivity is < 50mK (0.05°C), with a measurement accuracy of +/- 5°C in the -25°C to +125°C range. This is useful in performing search and rescue operations, where temperatures can be low and with small temperature differences. Live video is output with up to 1080p resolution (thermal video is scaled up), while stored recordings on an internal SD card have a resolution of 640x480 pixels for thermal and up to 4K for visual videos and pictures.

The angle of view for the RGB sensor is 56° x 45°, and for the thermal sensor, a lens with 45° x 37° was selected because it was the widest view of the three available lenses for the FLIR Duo Pro R. At 120m altitude, which is often the maximum according to regulations (see Section 8.2 for details), the thermal sensor’s field of view corresponds roughly to an area of 100m x 80m when looking straight downwards. Considering that ro-ro ships can be over 200m long, this means that the camera needs to be moveable independent of the drone to be able to “scan” the whole ship.

To be able to move the camera independently of the drone and also control it (e.g., changing settings), a 3-axis *gimbal* is used. The camera is mounted to the gimbal, which has motors to control the movement of the camera. An internal IMU in the gimbal, together with a stabilizer algorithm, provides stabilized video output.

The Gremsy Pixy U gimbal [21] was chosen as suitable for the FLIR Duo Pro R [22]. This gimbal, as shown in Figure 8, can be controlled from the autopilot with several MAVLink commands, for example for automatically aiming the camera at the desired ROI.

Figure 8 FLIR Duo Pro R thermal camera mounted on the Pixy U gimbal, image taken from Gremsy.com

6.2.6 Ground Station

The ground station hardware consists of a standard computer, a GNSS receiver with antenna (satellite-based positioning, we use the “F9P” from u-blox), and the HereLink controller (see Section 6.2.3) for communicating with the drone. The GNSS receiver and antennas are preferably mounted above any obscuring object, giving them free line-of-sight to the drone and satellites. For simple interaction with the drone system, the ground station should be accessible using a touch screen on the bridge like the one shown in Figure 9.

Figure 9 Example of a touch screen for displaying the drone system's user interface. Image taken from Bravour.com

6.3 Software Design

A high-level system architecture shown in Figure 4 is also reflected in the software design. The overall system consists of two communicating sub-systems: the drone and the ground station. The software on the drone is responsible for ensuring stable flight, providing information about the drone’s state and executing commands from the ground station. Even though modern flight controllers can execute complex pre-planned flights (perform so-called “missions”), the ground station performs the high-level control of the drone in our design like making the drone follow a trajectory around the ship while pointing the camera towards different regions of interest. As explained in Chapter 5, the main reason is that the drone’s movements are relative to the moving ship and constant communication needs to be maintained with the ground station anyways. The ground station further receives the video stream from the drone’s camera. It could further be processed, e.g., for smoke or missing person detection, but this is outside the scope of the presented prototype (see Section 6.1).

6.3.1 Drone Software

Onboard of the drone, we decided to run *PX4* [23]. PX4 is an open-source flight controller software that is mainly developed for Pixhawk flight controller hardware (see Section 6.2.2). It implements the motor control to maintain stable flight using the flight controller’s sensors. It further implements, MAVLINK communication with other components onboard of the drone and towards the ground station, as well as autopilot functionality like orbiting a specific point or executing pre-planned flights. While alternative flight controller software with similar functionalities exists, only PX4 is fully supported by *MAVSDK* [24]. MAVSDK is a software project that simplifies communication with drones from a computer. As explained in the next section, MAVSDK was identified to support the effective development of the ground station for the targeted use cases on ship.

On our drone prototype, we used an unmodified version of PX4 version 1.12.3. Instead of using the autopilot functionality of PX4, however, we implemented an autopilot specifically for the targeted use cases within our ground station software Control Tower which sends low-level commands (moving to a certain point or at a certain velocity) to PX4. This approach is detailed in Section 8.1.1.

6.3.2 Ground Station Software

Within the ground station, two different software applications were used for two different purposes:

1. Performing calibration of the drone's sensors and general configuration of the drone
2. Realizing the use cases presented in Chapter 4, including control of the drone and user interface

For calibration and configuration purposes (1.) and initial test of the drone, "QGroundControl" was used. The targeted use cases (2.) were realized using an in-house open-source project called "Control Tower".

6.3.2.1 QGroundControl

QGroundControl is an open-source ground station software that supports full configuration, flying and flight planning of flight controllers that communicate via MAVLink. It is closely developed with the PX4 flight controller software within the Dronecode foundation. QGroundControl runs on mobile devices (Android, iOS) and desktop computers (Windows, macOS, Linux). It provides an easy-to-use user interface as shown in Figure 10. It further provides advanced features like setting up an RTK GNSS base station. The main development target is a tablet device, therefore, using it via a touch interface [25].

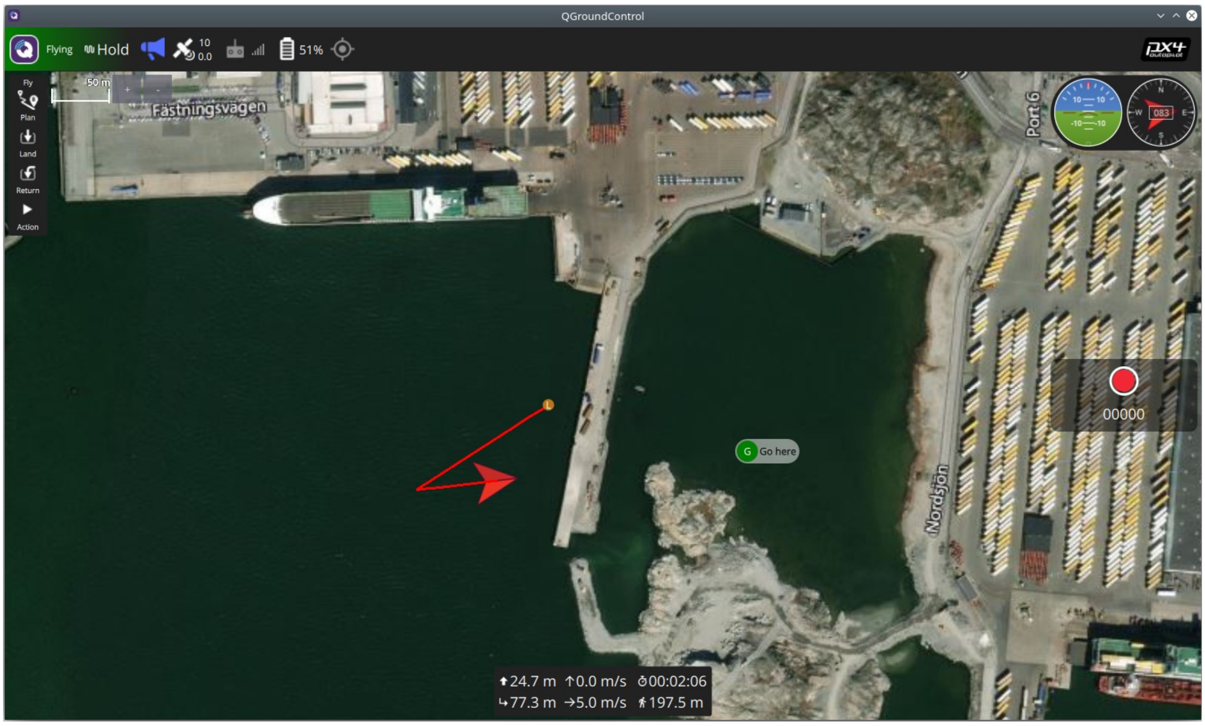

Figure 10 QGroundControl user interface

From a development point of view, QGroundControl is quite complex as a result of the wide range of vehicles, functions and target devices it supports. At the same time, implementing the use cases of this project, especially where routes follow the moving ship, would have meant quite fundamental changes in QGroundControl. Therefore, we decided it was more effective to create a separate prototype application "Control Tower" that specifically implements the use cases.

6.3.2.2 Ground Station Prototype based on MAVSDK & WayWise – Control Tower

Control Tower is our in-house developed ground station software that is built on MAVSDK and *WayWise*[13], our in-house open-source rapid prototyping library for connected, autonomous vehicles. MAVSDK is a software development library for communication with MAVLink-based systems, mainly drones. It allows controlling the drone and its payload, e.g., camera and gimbal, as well as receiving information about the drone's current state. MAVSDK makes it possible to perform actions like take off, movement to a specific point and landing with the drone using few lines of code and without requiring knowledge about the MAVLink communication that is performed in the background. The combination of results from previous projects in our WayWise library with MAVSDK enabled us to perform rapid prototyping of the specific functionality needed for realizing the targeted use cases of fire patrol, fire resource management and search & rescue (see Chapter 4 and Section 5.2).

With this report, we release the Control Tower research prototype as open source[14]. Control Tower is detailed in Section 8.1.1 as part of the technical feasibility analysis.

6.4 Simulation

Simulated worlds were used for two purposes in this project: early development and drone pilot training. All functions of Control Tower (see previous section) were first developed using simulation before testing with a real drone. Simulation is very time- and cost-effective compared to testing in reality, but of course, field tests were performed as well before testing on ship.

The PX4 flight controller software (see Section 6.3.1) is supported by several simulators ranging from a simple plane world to visually and physically realistic simulations with various weather conditions. We used the simulators "jMAVSim" [26] and "Gazebo" [27], which are both open-source projects. jMAVSim is a simple computationally lightweight simulator for flying quadrocopters in a plane world that does not contain any other objects but the ground and the quadrocopter itself. It is easy to run and was therefore used for early development and testing as well as demonstrating the Control Tower UI. Gazebo is a powerful simulator that is widely used in the robotics community. It supports complex worlds, virtually any kind of vehicle and physics simulations. Gazebo was mainly used for testing camera functionality and simulating the landing approach on a moving ship (detailed in Section 8.1.4). Both jMAVSim and Gazebo were used with *software in the loop* (SITL) simulation with PX4, where PX4 was run on a computer (instead of flight controller hardware) for pilot training and Control Tower development. Control Tower does not differentiate between PX4 in SITL or running on a real drone. In both cases, MAVSDK is used to communicate to the (virtual or real) drone via MAVLink.

[13] https://github.com/RISE-Dependable-Transport-Systems/WayWise
[14] https://github.com/RISE-Dependable-Transport-Systems/ControlTower

6.5 Cost Estimate

Following the presented design decisions, we can summarize the costs based on the Acecore Zoe drone (introduced in Section 6.2.1). The cost estimate for the drone is shown in Table 3, the estimate for the ground station in Table 4.

Table 3 Cost estimate for drone incl. sensors

Item	approx. cost in € excl. VAT
Drone base: Acecore Zoe development kit	6.000
Communication (video stream & MAVLink): Herelink HD (or similar)	600
Dual GNSS RTK receiver (yaw estimation without compass): 2x Holybro H-RTK F9P Lite (or similar u-blox F9P based receiver)	800
Gimbal: Gremsy Pixy U	1.800
Thermal & RGB Camera: FLIR Duo Pro R	6.300
Battery monitoring: MAUCH PL Sensor Hub X2 and sensors	300
Battery: 2x Tattu LiPo 22000mAh	1.000
Cabling, mounting details	200
Sum	17.000

Alternatives, especially to the chosen drone base, exist in case the weather resistance requirements defined in Table 2 should be exceeded. The chosen drone, Acecore Zoe, is a quadrocopter. Alternatives from the same manufacturer with 6 rotors (Acecore Noa) or 8 rotors (Acecore Neo) provide higher redundancy for motor failures and even higher wind tolerance (up to 35 knots, 40 knots gusts with Neo) at a higher cost (approx. 10.000 € for Neo, approx. 13.000 € for Noa) [28]. Noa provides wind tolerance of up to 28 knots, 35 knots gusts with comparably high flight times of up to 60 minutes.

Instead of a single GNSS RTK receiver, the drone cost estimate includes dual GNSS RTK receivers to obtain the drone's estimated heading without relying on a compass. This is an anticipation of the feasibility analysis detailed in Section 8.1. Compasses are subject to interference by the ship's metal structure as shown in Section 8.1.6.2.2. During the feasibility analysis itself, a single GNSS RTK receiver was used.

Table 4 Cost estimate for ground control station

Item	approx. cost in € excl. VAT
Rugged All-In-One Computer with Touchscreen	2.000
GNSS RTK receiver: Holybro H-RTK F9P Base (or similar u-blox F9P based)	500
Communication (video stream & MAVLink): Herelink HD (or similar)	500
Sum	3.000

It must be noted that the total cost of approx. 20.000 € for the drone system includes hardware costs only, without certification of either software or hardware. Ensuring that all regulations are followed can be time-consuming and induce considerable costs (legal feasibility is discussed in Section 8.2). All the software used within the system is available as open-source projects. However, on-ship integration and software adaptation for the specific deployment will still lead to additional costs.

Further hardware is required for automated charging and storing the drone safely and will at least double the total hardware costs (when integrating fully autonomous and certified systems like the Skycharge Skyport DP5[15]).

Maintenance requirements will depend on the specific deployment and are hard to estimate before conducting long-term tests. Some maintenance will surely be required due to wear on moving parts as well as the batteries, and due to weather influences. We expect it to be infrequent (approx. once a year) and schedulable with other ship maintenance.

In summary, while the presented prototype system, which is the basis for the analyses in the following chapters, costs less than 20.000 €, we expect costs to rise considerably when the system undergoes productization. It needs to be completed with a drone docking station, which can easily double the costs. Further, deployment-specific adaptations, certification and increased weather resistance are considerable price factors. Especially certification is a cost risk which can, however, be amortized over several deployments. When deploying several instances of the drone system (10 or more) and keeping costs for the drone docking station low, e.g., by cooperating with a suitable supplier, an overall price tag below 50.000 € per deployment might be achievable but challenging.

[15] https://www.skycharge.de/

7 Demonstration and Validation Setup

In order to gather input for the feasibility as well as usefulness analysis, field tests on land and a demonstration on board the DFDS Petunia Seaways were performed. Field tests on land were performed continuously during the development of the drone system. As mentioned earlier, due to the COVID-19 pandemic it was first possible for us to test on ship 5 months before this report was due. Therefore, the majority of tests were performed on land. In the following, we will describe our safety measures, the final demonstration setup and, finally, discuss the validation and reproducibility of results.

7.1 Safety Measures

To maintain personal safety, avoid disturbing other traffic and protect expensive equipment, we maintained several safety measures and followed regulations. Since 1st of January 2021, EU-wide drone regulations were introduced [29]. Therefore, only licensed drone pilots flew during the project. RISE is a registered drone operator and accordingly, our drones were labelled with the operator ID. The pilots trained using simulation (see Section 6.4) and using smaller, cheaper drones[16] before flying the prototype drone (Acecore Zoe, see Section 6.2.1). Similarly, new features in development were always tested in simulation and on the small drones first. At all times, the pilot was accompanied by at least one other person. While testing autopilot functionality, the pilot's manual input did always have priority. Manual input would stop the autopilot and override previous control requests from it.

All flights were performed in the "Open Category – A3" of the EU drone regulation [29], i.e., the drones were under 25 kilograms total weight, remained within line of sight and below 120 meters altitude. Furthermore, a safety distance of at least 150 meters was maintained towards residential, commercial, industrial or recreational areas and, especially, towards people who did not explicitly agree to be in proximity of the drone. See Section 8.2 for more details on regulations.

We further prepared a safety checklist (based on the Swedish pilot training material [30]) that was applied before any test. The checklist can be found in Section 14.1.

7.1.1 Safety Measures on Ship

Before the on-ship flights on DFDS Petunia Seaways, the ship's crew was informed about the tests. Even here, a small drone was brought along. Before flying, both drones (the small one and the actual prototype) were calibrated. The small drone was tested first to make sure there are no unexpected problems. All flights were performed during the crew's lunch break to avoid interfering with the crew's work.

7.2 Demonstration Setup

The purpose of the on-ship demonstration was to test the prototype system in a relevant environment as well as to gather feedback, pictures, and videos for the usefulness analysis (see Chapter 9). The demonstration was performed on the 15th of June 2022 on DFDS Petunia Seaways, which was docked in the port of Gothenburg. As the port of Gothenburg is within the controlled airspace of the Säve airport, the maximal altitude for the flights was limited to 50 meters. The weather was sunny, around 17°C with a gentle breeze of around 5 m/s.

[16] *Holybro X500* quadcopter that weighs below 1kg (without battery) and costs approx. 450€ including Pixhawk flight controller

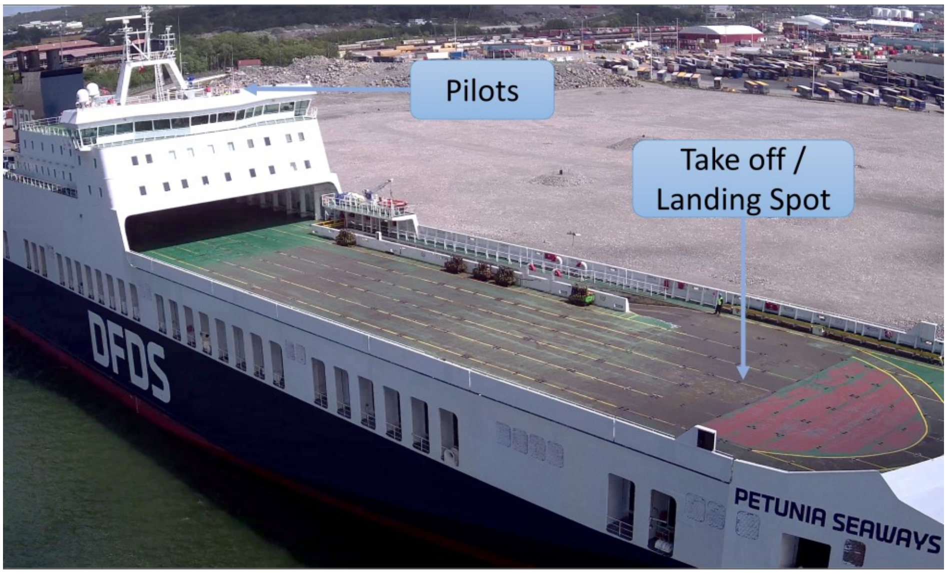

Figure 11 Demonstration Setup on DFDS Petunia Seaways

An overview of the demonstration setup is shown in Figure 11. Two team members were controlling the drone from the ship's monkey island, one pilot controlling the drone and the other controlling the gimbal and camera. The take-off and landing spot for the drones was located on the weather deck, where another team member and a supporting crew member from DFDS were located. During the time slot that was available for testing, the weather deck was virtually empty (as shown in Figure 11).

While it was verified that the drones would be able to fly autonomously by logging sensor data and running Control Tower (see Section 6.3.2) in the background, the flights were performed manually. Thus, the technical feasibility description of the operational modes is mainly based on field tests on land (Sections 8.1.2 and 8.1.3). The sensor data is reviewed in Section 8.1. Visual and thermal videos were recorded with the drone-mounted camera that give an impression of the live video feed that the drone system would enable. The videos were used in a questionnaire that is discussed and the results evaluated in Chapter 9.

7.3 Validation and Reproducibility

The gathered sensor data was reviewed using "Flight Review"[17], an online tool that is developed by the PX4 team (see Section 6.3.1). Further, the PX4 team provides information on how to detect problems with the drone or sensor interferences with Flight Review[18]. The recorded sensor data from on-ship flights was compared to similar flights on land, some interferences were detected that are described in the following section.

As detailed in Section 6.2, our drone design is based on off-the-shelf components and open standards as far as possible. All software used is available as open-source projects. The main problem of reproducing the tests would therefore be to get permission to fly on a vessel.

[17] https://logs.px4.io/

[18] https://docs.px4.io/v1.12/en/log/flight_review.html

8 Assessment of Feasibility

8.1 Technical Feasibility

The drone system designed for the following technical feasibility analysis was described in Chapter 6. As motivated there, we implemented the LASH FIRE use cases of a drone on deck in our in-house ground station prototype called Control Tower. In the following, we will first introduce Control Tower in more detail. Then, the technical feasibilities of the drone system's four operational modes (*Fly to Coordinate*, *Hover*, *Global Mission* and *Relative Mission*) presented in Section 5.2 and the underlying system requirements presented in Section 4.4 are reviewed based on data and experiences gathered during simulation, test and demonstration (see previous chapter for setup description). Specific sections are dedicated to automated take-off and landing, video streaming, as well as sources of interference in communication and positioning. Finally, the impact on the more general technical feasibility of the use cases and open questions is discussed.

8.1.1 Control Tower

We implemented the ground station prototype Control Tower to specifically target the LASH FIRE use cases. It is implemented in the C++ programming language using the Qt GUI toolkit[19], and based on MAVSDK and *WayWise*[20], see Section 6.3.2.2 for details. A screenshot of the prototype is shown in Figure 12. A map based on OpenStreetMap[21] and OpenSeaMap[22] is presented to the user that includes information about seamarks. The drone is shown as a red arrow and similar to the landing spot highlighted by a constant size, regardless of the user's zoom level. The user can zoom and interact with the map using touch gestures, e.g., pinch zoom.

The area on the right side of the map provides more advanced planning, configuration and control features that are used to prepare and adapt the system for a specific application. Once the system is set up, this area is hidden from the user.

Control Tower can connect to a real or simulated drone through MAVSDK (see Section 6.3.2.2). To connect to real drones, a telemetry radio needs to be connected to the computer running Control Tower (see Section 6.2.3). The high-level logic for controlling the drone, i.e., an autopilot that can execute missions (following a list of coordinates, controlling camera and gimbal) is also implemented in Control Tower. While PX4 also provides autopilot functionality, we only use it for the low-level control that is required to move the drone to a certain point. Placing the autopilot into Control Tower meant that we could implement missions relative to the moving ship without needing to adapt PX4 running on the drone. In any case, the ship's movements continuously need to be accounted for when planning the drone's movements. Thus, one might fear that the design choice of having the autopilot in the ground station software introduces the risk that control is lost in case of connection loss, but connection losses are always a problem that could lead to the drone crashing.

[19] https://www.qt.io/
[20] https://github.com/RISE-Dependable-Transport-Systems/WayWise
[21] https://www.openstreetmap.org/
[22] https://openseamap.org/

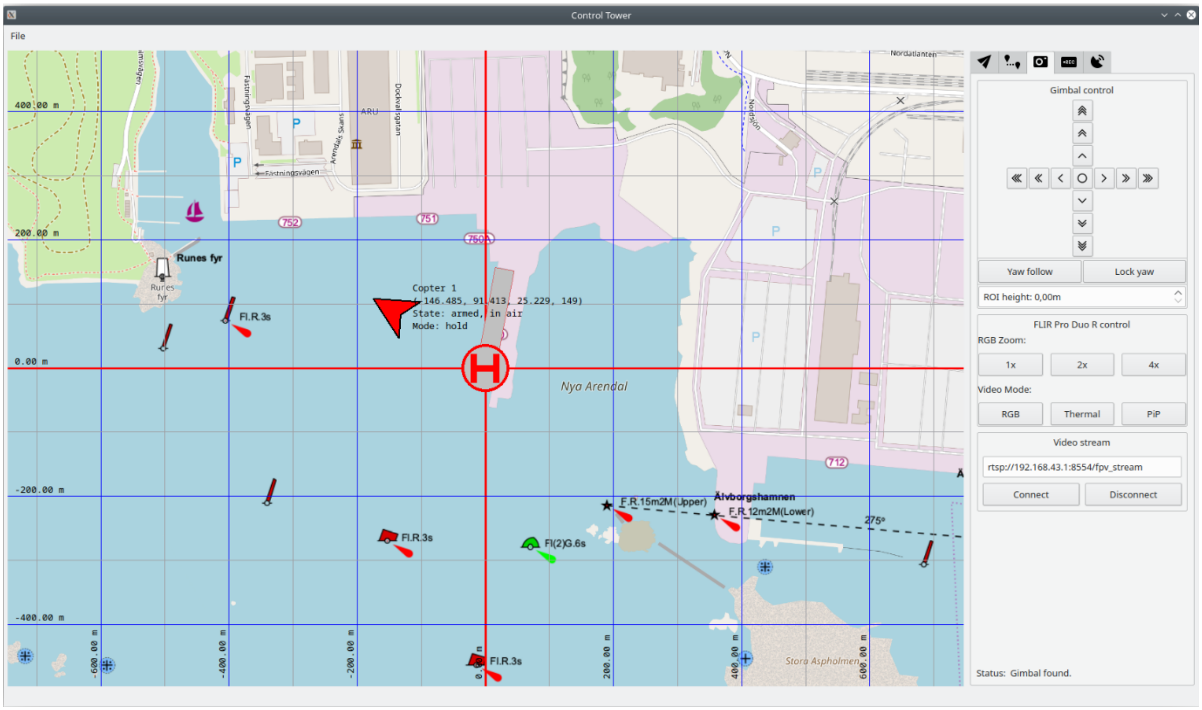

Figure 12 Control Tower prototype showing, map overview as well as camera and gimbal controls

The following functionality has been realized in and tested with Control Tower:

- Making the drone take off and land with the press of a button
- Making the drone move to and hover at a specific point on earth and relative to a moving reference (located on the ship when the system is deployed)
- Making the drone follow a pre-planned flight mission in global coordinates and relative to a moving reference
- Pointing the camera to a ROI by controlling the gimbal
- Direct camera control using joysticks (gamepad)
- Switching between different modes of the camera: visual light image and thermal image in different colour schemes, as well as zooming (2x and 4x)
- Providing a touch interface to the user that does not require expert knowledge
    - Showing a map with a focus on status information of the drone (position, orientation, altitude, camera's ROI) but also showing the ship's outline and optionally seamarks
    - Semi-manual control, i.e., the user can control the drone, but the system makes sure the control is safe, e.g., by controlling the altitude
    - Moving the drone and setting camera ROI using touch gestures on the map
- A more advanced user interface for planning a flight and saving as well as loading plans
- Experimental features for specific parts of the feasibility analysis, mainly for testing moving base RTK GNSS (see Section 6.2.4)

Control Tower is fully functional, and we develop it as an open-source project[23]. It needs to be noted, though, that it is a research prototype, and its main purpose was to perform the feasibility and usefulness analysis of this project in contrast to implementing a finished product for broader use.

[23] https://github.com/RISE-Dependable-Transport-Systems/ControlTower

8.1.2 Operational Modes: Fly to Coordinate and Hover

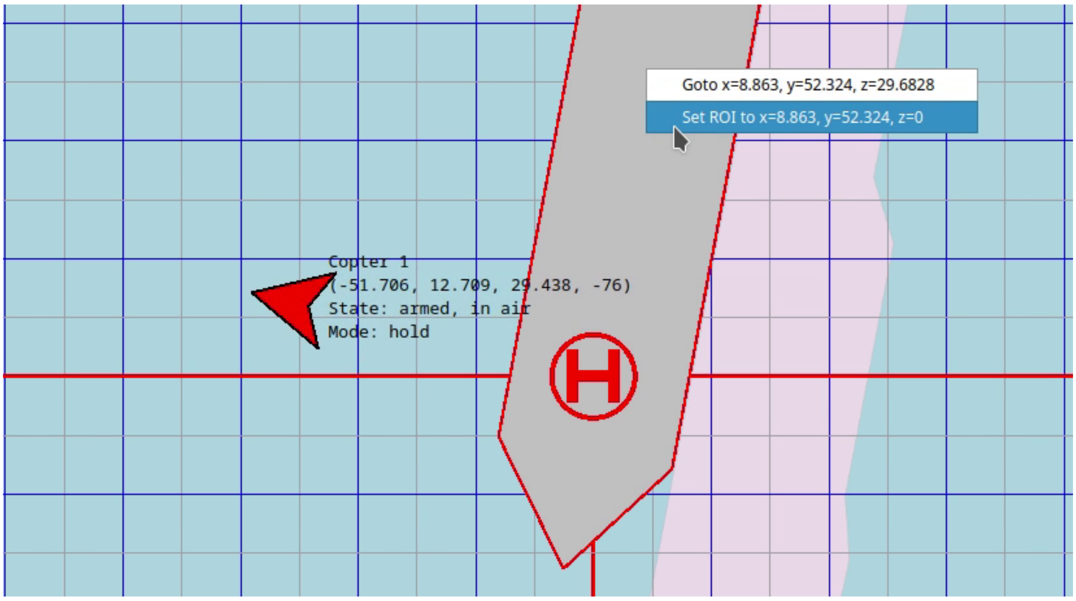

Figure 13 Control Tower user interface showing how the drone is controlled from the map

From a user perspective, the *Fly to Coordinate* and *Hover* modes behave very similarly. The user interface is shown in Figure 13: Control Tower shows a map on which the user can execute 'Goto' or 'Set ROI' requests by tapping (touchscreen) or clicking (mouse) on the desired location. In case of a 'Goto' request, the drone itself will move to the location, in case of 'Set ROI' the gimbal will point the camera to it.

From an implementation perspective, the two modes are quite different. *Fly to Coordinate* is a singular request containing location information that is sent to the drone. It is a standard functionality of PX4 (or any other modern flight control software) and MAVSDK on the ground station side. Thus, it is straight-forward to implement.

Hover requires the drone to constantly reposition itself ('Goto') or the camera ('Set ROI') when the ship is moving. Conceptually, periodic *Fly to Coordinate* requests are sent, where the requested position is updated with information about the ship's movements that need to be tracked in Control Tower (details in next paragraph). On a lower level, different functionality is used, however. *Hover* needs to constantly mirror the ship's movements by sending velocity requests (instead of position requests) to the drone. When the target position on ship is updated, the target position will move with the ship while the drone is repositioning, and the velocity requests sent to the drone need to account for this. Repositioning the drone to locations relative to the ship is a sub-functionality required in the *Relative Mission* mode and further details on its implementation using the *pure pursuit* algorithm [31] are provided in the following section.

As mentioned in the previous paragraph, the ship's movements need to be tracked in Control Tower to enable the drone to position itself relative to the ship. Therefore, a point of the ship is tracked using GNSS and used as a position reference when calculating velocity requests for the drone. We use an RTK-capable GNSS receiver (see Section 6.2.4) and while RTK moving base can be used to achieve cm-accurate positioning of the drone relative to the ship, we see it as unnecessary for in-flight positioning. RTK moving base requires a high bandwidth on the communication link between base station and flight controller (see Section 8.1.4), does not tolerate lost messages well and the accuracy provided by dual band GNSS receivers like the u-blox F9P used in this prototype is fully sufficient for in-flight positioning.

In summary, some development for the *Hover* mode was required to let the drone track a moving position reference. In general, however, both modes were shown to be technically feasible with the prototype presented in Chapter 6, i.e., with off-the-shelf hardware and open standards.

8.1.3 Operational Modes: Global Mission and Relative Mission

Comparable to the *Fly to Coordinate* and *Hover* modes, the *Global Mission* and *Relative Mission* modes are similar from a user perspective but differ in their implementation. The *Global Mission* mode that deals with global coordinates is a standard functionality of PX4 and MAVSDK but the *Relative Mission* mode that deals with coordinates relative to an on-ship reference point is not.

For both modes, the user can create lists of coordinates by interacting with the map in Control Tower, see Figure 14. At each coordinate, a command can be executed like pointing the camera to a new ROI or switching between the thermal and visual view of the streamed video. Once the mission planning is completed, it can be sent to the drone. Furthermore, the plan can be saved to be loaded and edited later on. The process of planning a mission is only required when setting the system up for a specific vessel and would presumably be performed by the company providing the drone system and not the ship's crew.

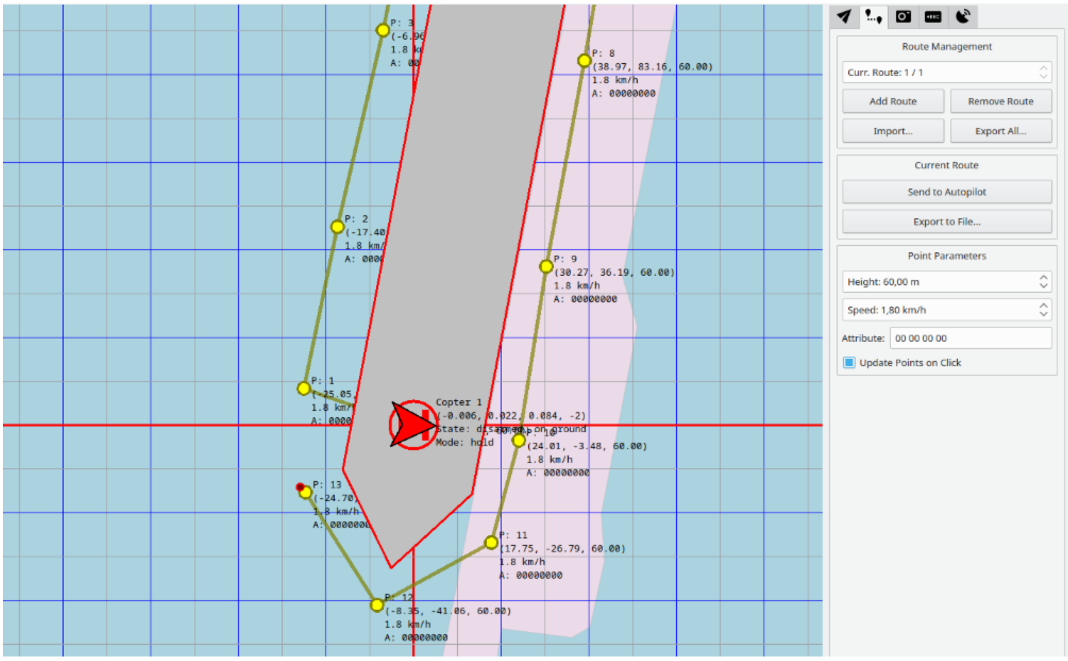

Figure 14 Example of route created in Control Tower (yellow dots connected by lines)

As mentioned in the previous section, we implemented the pure pursuit algorithm [31] in Control Tower to realize the autopilot functionality required. We provide a brief description in the following, but the interested reader can find the implementation in our open-source release of Control Tower[24]. Pure pursuit is a widely used algorithm for ground-based robots. Its purpose is to make the robot follow a provided route in a 2D plane. It can be visualised as in Figure 15, a circle is drawn around the robot's current position (big blue dot) and the intersection of the circle and the route (black line) is the current goal (small orange dot) until the next periodic update. The calculation is looped, usually with a few tens or hundreds of milliseconds period. Depending on the kinetic model of the targeted robot (e.g., servo-steered wheels like Ackermann, or differential drive), a curvature or velocity vector (like the orange arrow) is obtained from the current goal that is then used to update the control of

[24] https://github.com/RISE-Dependable-Transport-Systems/WayWise/blob/master/autopilot/purepursuitwaypointfollower.cpp

the robot (e.g., steering angle and wheel speed). The size of the circle around the robot is a parameter that determines how closely the algorithm tries to match the given route. A bigger radius will give the algorithm more freedom to cut corners and, thus, smoothen the resulting track driven by the robot.

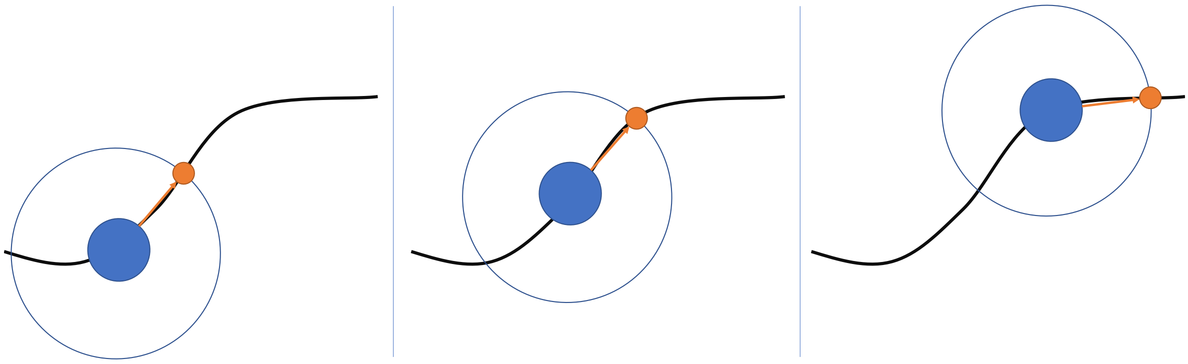

Figure 15 Example of pure pursuit showing three steps of an abstract robot following a path

In our case, we let the drone fly missions at a fixed altitude and can thus apply pure pursuit in the xy-plane even though the drone navigates a 3D space. The route is obtained by drawing lines from one coordinate in the mission to the next one in the list. Between different iterations of pure pursuit, not only the drone can move but the route itself as well (as the route is relative to the moving ship). In our simulations and tests with a remote-controlled car as a reference point (instead of a ship), this was handled well by pure pursuit but when a constant velocity of the drone relative to the moving reference point is desired, the reference point's velocity needs to be accounted for in the calculations. For this, a GNSS receiver connected to Control Tower is still sufficient to estimate the reference point's velocity: the reference point (the moving ship) is not expected to turn or accelerate drastically and therefore, the velocity can be approximated well by calculating the difference between two consecutive position estimates obtained from the GNSS receiver.

Special cases of pure pursuit, e.g., when the circle does not intersect the route, are usually handled by drawing a line from the drone's current position to the closest point on the route and following the result (applying pure pursuit to it). This is also how the *Hover* mode described in the previous section is implemented with the special case that the route only consists of a single coordinate (the current position target) and never finishes (following the route only ends when the *Hover* mode is left).

In summary, while the *Global Mission* mode is standard functionality in modern flight controllers, the *Relative Mission* mode required some implementation and testing. Further testing is required on a sailing vessel, especially, in strong or severe weather. In general, however, both modes are technically feasible using the prototype system presented in Chapter 6.

8.1.4 Automated Take-off and Landing

The previous sections focused on the drone's operational modes in flight and a general theme was that custom implementations are required as soon as the drone needs to position itself relative to the moving ship. This is similarly true for automated take-off and landing, where too the ship's movements need to be accounted for in the drone's control. Both operations are more dangerous, though, due to the proximity to other equipment and potentially people. The main challenge is landing the drone when a drone docking station for automated charging is targeted (see Section 5.1), due to the high precision required. For this purpose, we evaluated the "Precision Landing" feature of PX4 [32] in simulation using Gazebo (see Section 6.4), an example is shown in Figure 16. In our implementation, a box that represents the drone docking station is moving inside Gazebo. The box's current position is communicated to the Precision Landing function on the drone using Control Tower (this is called "precision landing on a moving target provided by an offboard positioning system" in PX4). We evaluated various parameters (box velocity, configurations of Precision Landing) and were eventually able to get the drone to land on the moving box. However, the functionality proved quite unstable under varying parameters, often causing the drone to simply go straight down instead of following the provided landing target. We assess that a custom landing functionality would need to be developed that specifically targets the use case of landing on a moving ship, including rigorous testing.

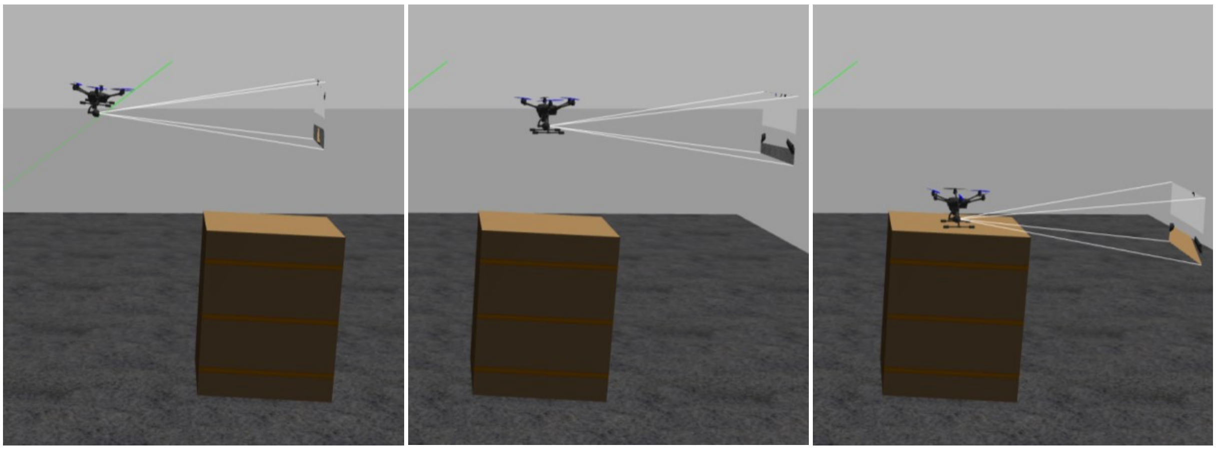

Figure 16 Example of a precision landing approach using the PX4 flight controller and Gazebo simulation environment

In the simulation, the simulation environment can simply report the position of the moving landing target. In reality, a suitable sensor is required. Potential approaches are visual (camera or IR beacon and sensor) or RTK GNSS-based (see Section 6.2.4 for more details). Visual approaches could be incorporated in the drone docking station for improved weather protection, e.g., a camera that is only exposed to weather when the drone approaches. The RTK GNSS-based approach has the advantage that no additional equipment is required and that the influences of environment and weather are limited compared to visual approaches (e.g., dirt, salt, rain or snow). We performed initial tests of RTK GNSS in moving base mode, achieved centimetre precision and generally promising results. The disadvantages, however, are the high bandwidth as well as low latency required for the wireless communication link between the drone and the base station with their respective GNSS receivers. Additionally, the drone's estimated position might jump, e.g., when messages between drone and base station are delayed. The high bandwidth required stems from the fact that an as-high-as-possible position update rate is required during landing and RTK messages need to be received for each update. This is in contrast to RTK with a fixed base, where RTK messages at 1 Hz are sufficient even when calculating position updates at 10 Hz. For example, when calculating position updates at 8 Hz with RTK moving base, the wireless communication link needs to support approx. 45 KiB/s (460800 baud) with a maximum latency of approx. 75 ms [33] for RTK messages alone. It needs to be made sure that control data and video streaming do not interfere with that. In summary, the RTK GNSS based approach is more experimental than visual approaches in this context, but both are technically available on the market.

Overall, automated take-off and landing are critical and dangerous operations. Further research and development are required to obtain a robust approach for the use case of landing on a moving ship under all kinds of environmental influences that can occur.

8.1.5 Video Streaming

Streaming live video from the drone-mounted combined visual and thermal camera (FLIR Duo Pro R, see Section 6.2.5) was tested extensively on land and on board the DFDS Petunia Seaways (see setup description in previous chapter). A single video output is provided by the camera and the user can switch between visual or thermal view and different zoom levels (1x, 2x, 4x) through the press of a button in Control Tower. The video is transferred through the HereLink system (see Section 6.2.3) with a resolution of 1920x1080 at a 30Hz refresh rate and a latency of a few hundred milliseconds. In parallel, the visual and thermal video can be recorded in the individual sensor's native resolution of 640x480 and 3840x2160, respectively. Sample images can be seen in Figure 17 to Figure 22.

The HereLink communication system proved to be very reliable during our tests for both control and video data. The FLIR Duo Pro R provided high-quality images and, especially, the details of the *relative* temperature differences shown in the thermal video were commented on very positively by the DFDS Petunia Seaway's crew on the day of the demonstration. For *absolute* temperature measurements, however, the camera needs to be calibrated quite precisely in order to get reasonable temperatures for pixels in the thermal image (including ambient temperature, humidity and emissivity of the measured materials). The calibration further needs to be performed with the help of a Bluetooth-connected app provided by FLIR ("FLIR UAS™", version 2.2.4 from 7th of October 2019, the most recent at that the time of writing, was used) that had several problems of crashes, preventing the camera to output video when connected, or simply connection problems during our tests. Consequently, we were unable to change the camera's configuration in flight, which limits the possibility to perform precise absolute live measurements in the targeted use cases. Optionally, thermal video can be recorded and processed offline to obtain absolute measurements. Relative temperature differences can nevertheless be sufficient for the use cases, e.g., to detect fire or a missing person at sea, because it is less important what temperature the fire or person have exactly. More important for automated detection is presumably the temperature contrast compared to surroundings.

We did not process the video stream further, but only recorded it for the usefulness evaluation of the following chapter (see also scope of this report in Section 6.1). During our tests, we did not perceive any notable obstacles for further processing the video stream in Control Tower, e.g., using AI-based solutions, to automate the detection of fire, smoke or a missing person in parallel to the drone's flight.

Figure 17 Visual image streamed from drone showing DFDS Petunia Seaways (no zoom)

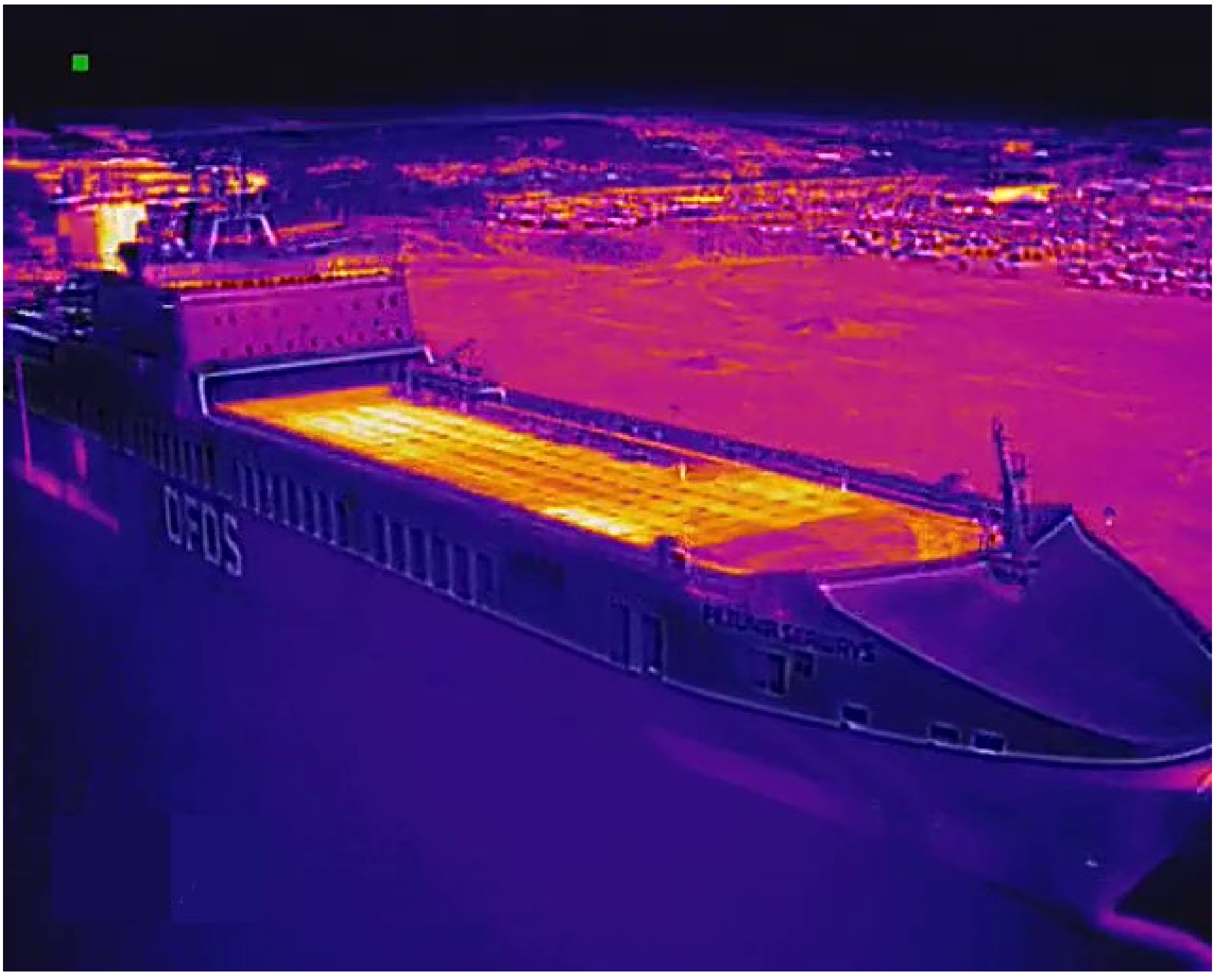

Figure 18 Thermal image streamed from drone showing DFDS Petunia Seaways (no zoom)

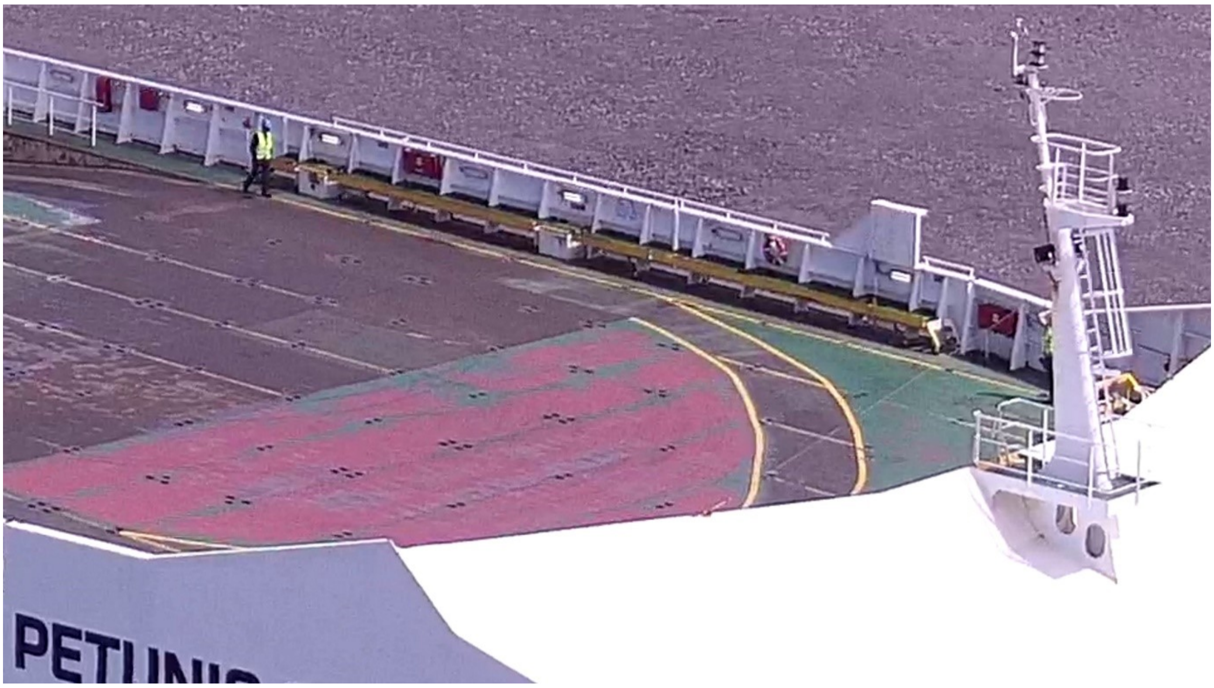

Figure 19 Visual image streamed from drone showing DFDS Petunia Seaways (4x zoom)

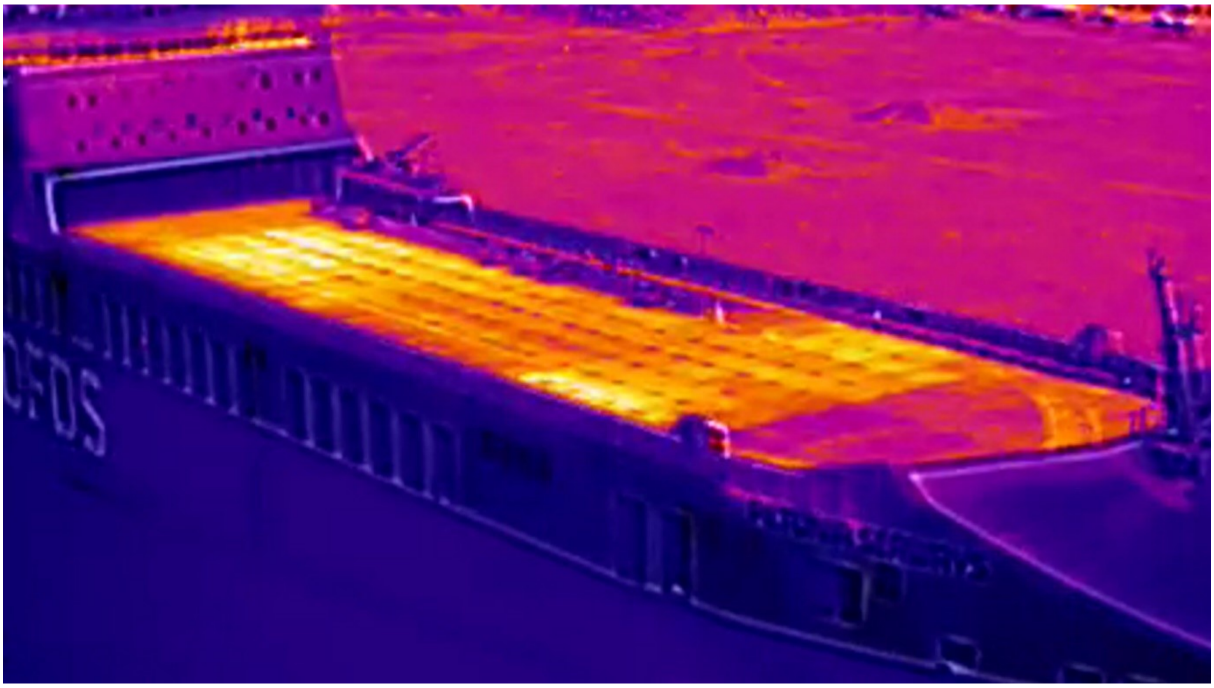

Figure 20 Thermal image streamed from drone showing DFDS Petunia Seaways (2x zoom)

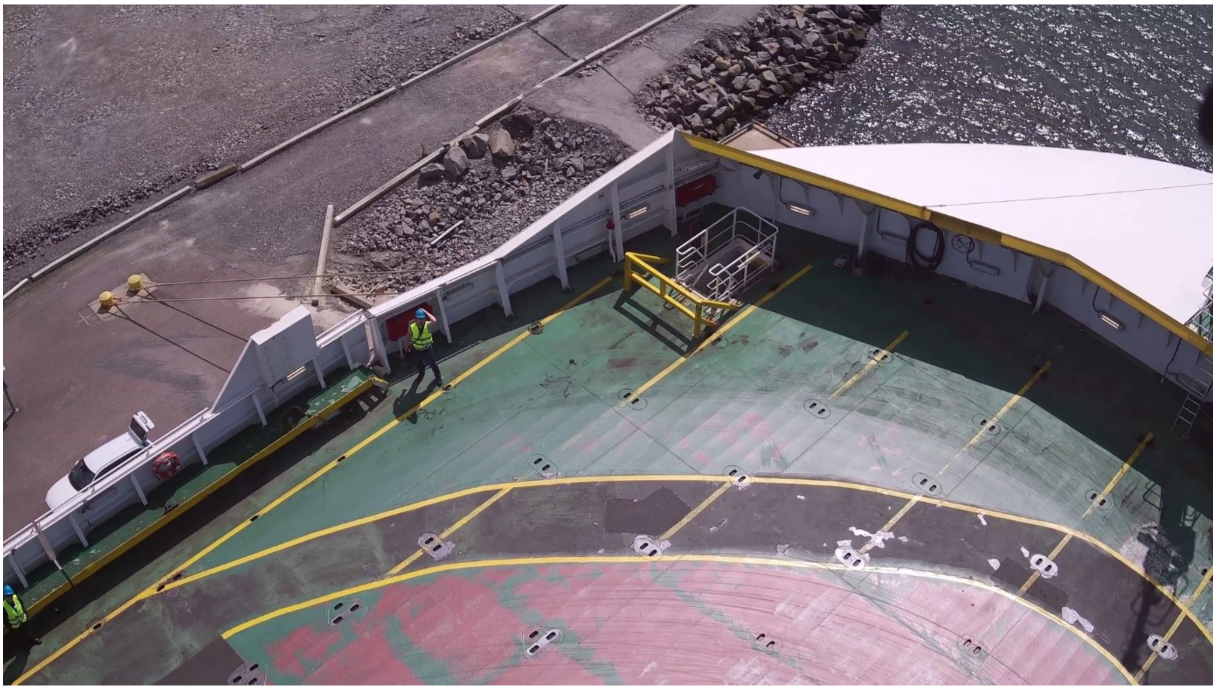

Figure 21 Visual image streamed from drone showing DFDS Petunia Seaways from another angle (no zoom)

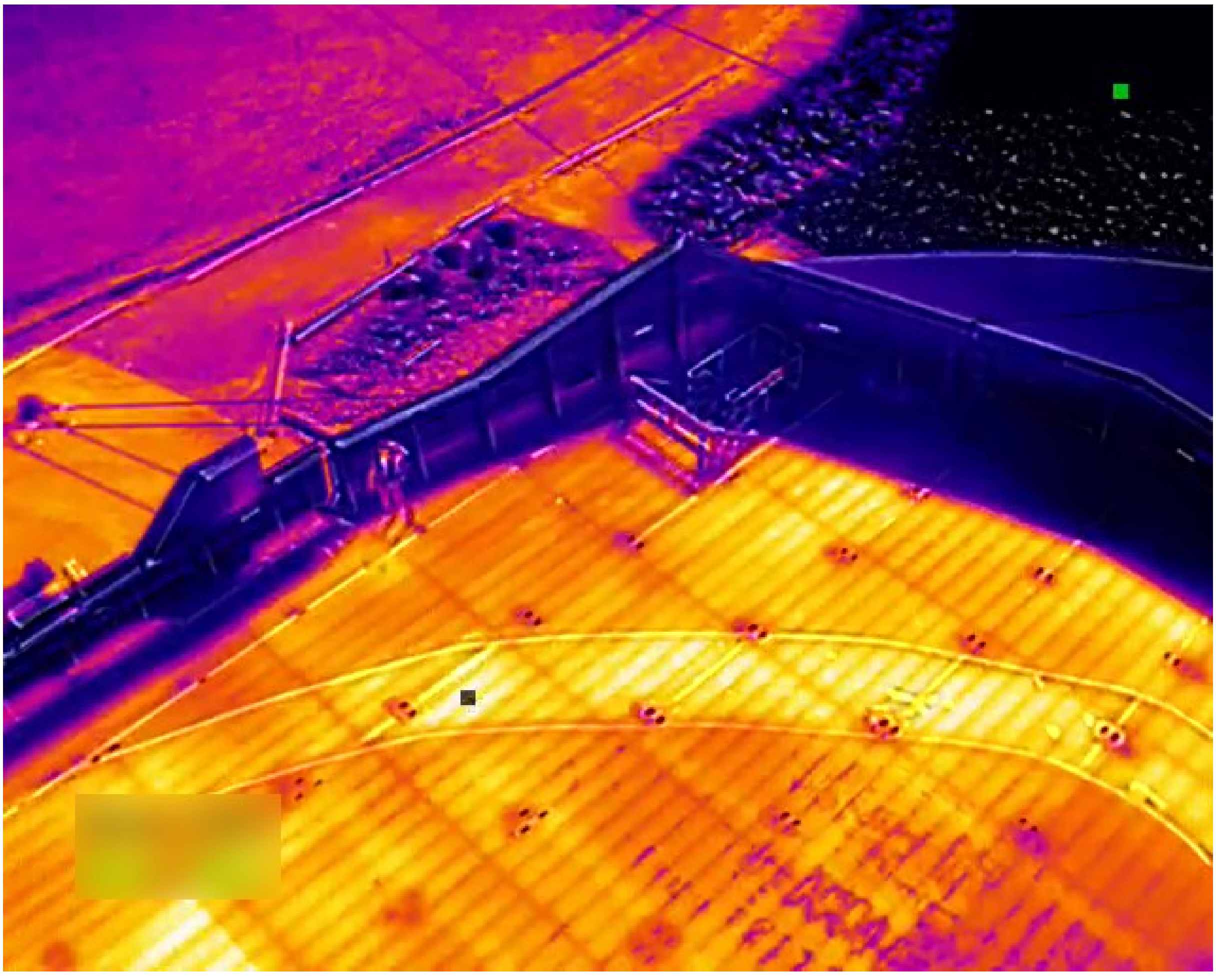

Figure 22 Thermal image streamed from drone showing DFDS Petunia Seaways from another angle (no zoom)

8.1.6 Electromagnetic Interferences

Given that a ro-ro ship is a huge metal construction with several hundred square meters of flat surfaces that have the potential to reflect signals needed for communication and positioning, interferences on these systems can be expected. Further interference might come from other equipment on board, e.g., radio communication and radar. Some remarks on electromagnetic compatibility (EMC) follow below, but an actual EMC analysis according to the Radio Equipment Directive [34] is out of scope and needs to be performed in future work.

8.1.6.1 Communication

The communication between drone and ground computer is performed within the 2.4 GHz ISM (industrial, scientific and medical) band in our prototype system (see Section 6.2.3). The ISM band is widely used for unlicensed low-power devices that communicate, e.g., via WiFi or Bluetooth [35]. The ISM band is contained in the IEEE S band range (2 to 4 GHz) that is used besides the X band for the ship's surface radar (8 to 12 GHz). Therefore, there is a wide range of sources of potential interference. We did not encounter any interferences during our tests, neither on land nor on ship. However, as the DFDS Petunia Seaways was docked during our demonstration, the radar (and other potential sources of interference) could have been running at lower power or shut off completely. Therefore, further tests and analyses are required.

In case the use of the ISM band would prove to be problematic, off-the-shelf alternatives exist for the MAVLink-based communication link for controlling the drone that rely on different frequency bands. They could also be used complementary to the ISM band to achieve redundancy. Solutions for digitally streaming live video mainly seem to use the ISM band and, potentially, a custom solution would be required.

In summary, the communication between ground station and drone was shown feasible with off-the-shelf components for the targeted use cases but some risks were identified, and a deeper analysis is required to ensure the absence of EMC problems.

8.1.6.2 Positioning

8.1.6.2.1 GNSS

Interference of the GNSS-based positioning used in our prototype was a concern because GNSS signals from satellites can be reflected by the ship's metal surfaces and lead to imprecise or even lost positioning information. We tested two different GNSS-receivers on the drone, the u-blox F9P described in Section 6.2.4 as well as the previous-generation and less-capable u-blox M8P (a single band receiver, whereas the F9P is a dual band receiver). We logged the number of satellites used during flight. Note that even though the indicators are called Global Positioning System (GPS), they are calculated based on the information from all available GNSSs. When using the F9P, we further logged the "GPS noise" and "GPS jamming" indicators reported by PX4. The number of satellites used was virtually constant during our on-ship flights with 15 to 16 and 30 to 31 satellites with the M8P and F9P, respectively. GPS noise and GPS jamming showed no irregularities and were at comparatively low levels.

To summarize, we could not see any indications of interferences on the GNSS-based positioning.

8.1.6.2.2 Magnetometer

The magnetometer on the drone relies on the earth's comparatively weak magnetic field to determine the drone's global orientation. It is easily interfered with by metal structures like the ship itself or electromagnetic fields, e.g., originating from cables or electric motors. Under interference, the orientation reported by the magnetometer might be offset or completely unusable and the flight controller will be unable to reliably determine where the drone is heading based on magnetometer information only. If interference is detected while the drone is landed, it will be unable to take off automatically. On ship, a dedicated take-off spot is allocated to the drone and the magnetometer can be calibrated in order to tolerate the given local interferences as long as they are static. Interference during flight will cause the flight controller to try to fallback to other information sources for determining the drone's heading, e.g., another magnetometer or consecutive GNSS positions when the drone is moving. If a fallback is not possible, the drone might start to drift or rotate in a certain direction, which is highly undesirable for the level of automation that we are targeting in this work.

During our test flights on DFDS Petunia Seaways, we could observe magnetic interference in the data logged from the magnetometer. An example is given in Figure 23. It shows the magnetic field's total strength[25] sensed by the magnetometer during a landing approach. From the beginning of the graph to approx. 3:10 the drone is at a constant altitude of approx. 25 meters. Then, it goes down at constant speed until it lands at approx. 3:35. Optimally, the magnetic field's strength should be constant throughout. It fluctuates, however, because of electromagnetic interference from the drone's own electric system and more importantly, the magnetic field gets considerably stronger when the drone gets closer to the ship. We could further observe the flight controller detecting these interferences and sporadically switching between the two different magnetometers on the drone for obtaining heading information.

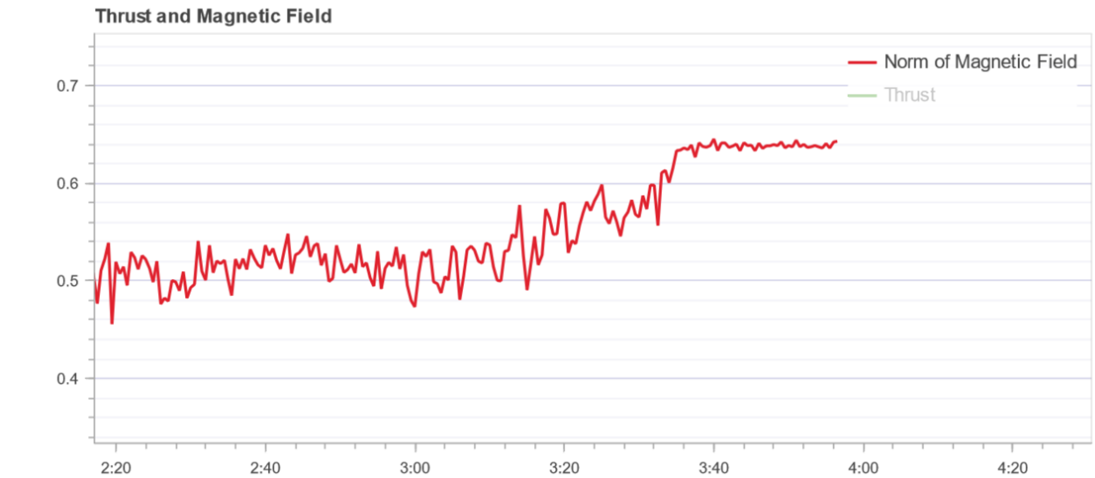

Figure 23 The drone's magnetometer is influenced by the ship's metal construction

While the flight controller could tolerate the magnetic interferences during our tests, we argue that a more robust solution than relying on magnetometer data is needed for determining the drone's orientation on ship. A suitable solution supported by modern flight controllers is the use of two GNSS receivers on the drone. Based on RTK GNSS (one receiver sends correction data to the other), the difference between the two GNSS positions received can be used to calculate the drone's heading and avoid the use of the magnetometer entirely[26].

In summary, due to the magnetic interferences we observed, we recommend avoiding using the commonly used magnetometer for determining the drone's heading by implementing a dual GNSS-based heading estimating solution.

[25] Norm of the x, y and z axes measured in gauss
[26] https://docs.px4.io/v1.13/en/gps_compass/u-blox_f9p_heading.html

8.1.7 Summary of Technical Feasibility of Use Cases

Table 5 gives a summary of the stated requirements for the drone system stated in Section 4.4 with feasibility assessments based on the discussions of this chapter and the system design presented in Chapter 6. Generally, the realization of a drone system for assistance in fire prevention, firefighting resource management and rescue operations was shown technically feasible using our prototype. The main requirement that needs further development is the automated take-off and landing (R7), where a robust approach for landing on a moving ship under all kinds of environmental influences is required. Risks were identified for the communication between drone and ground station (R5). The presented communication solution worked well during our tests, but further analysis of potential interferences and ensuring the absence of EMC issues are required. Finally, long-term testing of the system in the relevant environment, especially on a sailing vessel, is required to ensure that the system provides a high availability under various circumstances (R6).

Table 5 Feasibility analysis summary

Req	Description	Feasibility
R1	The drone needs to be able to position itself precisely.	Feasible
R2	The drone needs to be able to follow predefined paths.	Feasible
R3	The drone needs to be able to follow the ship's movements (positions and paths relative to the moving ship need to be supported).	Feasible
R4	The drone needs to be able to record and stream high-quality colour and thermal images and videos.	Feasible
R5	The drone needs to be able to communicate with the ship with long range (at least 1 km), high bandwidth (for live images) and relatively low latency to support relative positioning to the ship as well as timely notification of alarms.	EMC analysis & tests required
R6	The drone needs to be able to maintain high availability, even during severe weather.	Tests required
R7	The drone needs to be able to provide a high degree of automation and expect input from the crew only when desired by them. This includes especially automated take-off and landing.	Development & tests required
R8	There should be limited maintenance either in big time intervals only such that it can be performed when docked, or feasible with a limited amount of training.	Feasible
R9	The system should be useable by non-experts and require limited training only.	Feasible

This concludes the technical feasibility assessment. In the following, the legal feasibility of the drone system is analysed.

8.2 Legal Feasibility

The use of a drone in general, and especially on a ship for fire prevention and firefighting purposes, is regulated in various aspects. In the following, we provide an overview of the relevant standards within the EU and discuss the feasibility of operating the drone system legally for fire safety on board a ship[27]. Figure 24 gives an overview of the regulations discussed in the following.

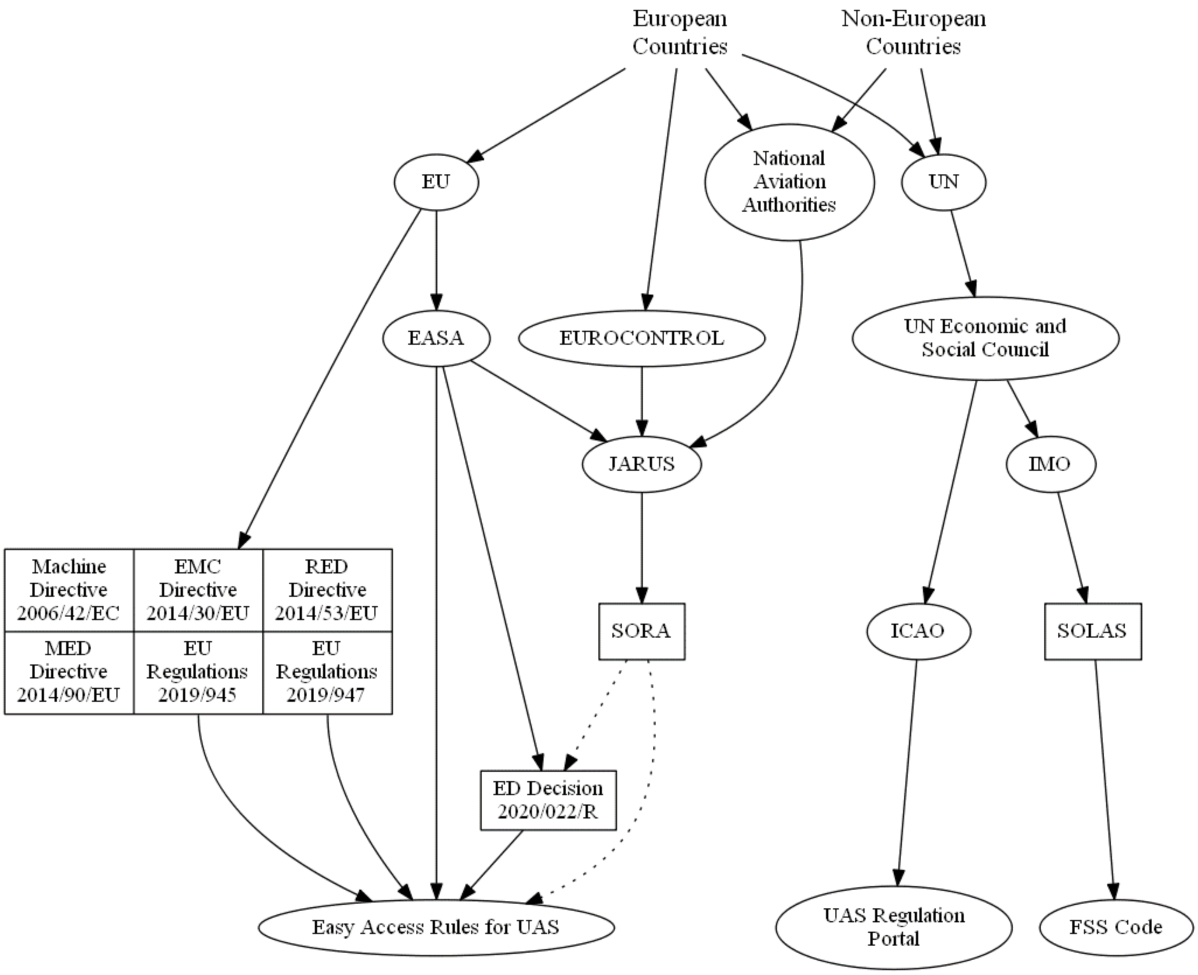

Figure 24. Overview of the discussed regulatory framework for drones on ships.

EU Regulations 2019/947 and 2019/945 [29] form the underlying framework which should ensure the safe operation of civil drones within the EU airspace. Complying with, e.g., the Machinery Directive 2006/42/EC [36] which states the relevant health and safety requirements, Directive 2014/30/EU on electromagnetic compatibility [37] and the Radio Equipment Directive 2014/53/EU [34] is also required for the CE-marking of the drone.

The Marine Equipment Directive (MED) 2014/90/EU [38] sets out performance and testing standards to be met by marine equipment placed on board an EU ship. The International Convention for the Safety of Life at Sea (SOLAS), 1974, as amended, specifies minimum standards for the construction, equipment and operation of ships, compatible with their safety [3]. The International Code for Fire Safety Systems (FSS Code) provides international standards for the fire safety systems and equipment [39] required by the SOLAS Convention.

[27] Note, that the terms 'drone' and 'unmanned aircraft system' (UAS) are used interchangeably within this chapter

In the following, we first provide an overview of EU airspace regulations applicable to drones. Then, we provide an overview of applicable regulations for the maritime context.

8.2.1 EU Regulations for Safe Operation of Civil Drones

The underlying framework which should ensure the safe operation of civil drones within the EU airspace is provided by EU Regulations 2019/947 and 2019/945 [29]. The regulations adopt a risk-based approach, i.e., the more dangerous the operation, the more stringent the requirements for the pilot and the operator. The regulations do not distinguish between leisure or commercial civil drone activities. They consider the weight and the specifications of the civil drone and the operation it is intended to conduct:

- *EU Regulation 2019/947 on the rules and procedures for the operation of unmanned aircraft* provides the following (Article 1):
  "This Regulation lays down detailed provisions for the operation of unmanned aircraft systems as well as for personnel, including remote pilots and organisations involved in those operations." [29]
- *EU Regulation 2019/945 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems* provides the following (Article 1):

  1. This Regulation lays down the requirements for the design and manufacture of unmanned aircraft systems ('UAS') intended to be operated under the rules and conditions defined in Implementing Regulation (EU) 2019/947 and of remote identification add-ons. It also defines the type of UAS whose design, production and maintenance shall be subject to certification.

  2. It also establishes rules on making UAS and accessories kit and remote identification add-ons available on the market and on their free movement in the Union.

  3. This Regulation also lays down rules for third-country UAS operators, when they conduct a UAS operation pursuant to Implementing Regulation (EU) 2019/947 within the single European sky airspace. [29]

Following EU Regulations 2019/947 and 2019/945 is required for any kind of drone use within the European Union. Different rules apply for drones belonging to different categories as defined by the regulations.

8.2.1.1 Drone Category and Operational Authorization

The categorization of drone operations is currently in a transition phase, where old regulations are phased out and new regulations come into effect from the beginning of 2024. During our test flights, we were able to fly within the 'open' category that is described in the following.

In the regulations applicable until the end of 2023, the 'open' category defined in EU Regulation 2019/947 is the main reference for the majority of low-risk commercial as well as leisure drone activities [40]. While this category does allow flights over uninvolved people for drones with a maximum weight of 500 g (subcategory 'A1'), they should not be expected (but can "happen") and direct overflights should be minimised. Since the drone used in our prototype system weighs just above 4 kg and can carry a payload of up to 5 kg (see Section 6.2.1), a total weight of 9 kg needs to be considered which means that the drone belongs to the subcategory 'A3'. According to the regulations applicable until the end of 2023, drones in that category are not allowed to fly near or over uninvolved people.

From 1st of January 2024, class identification labels ('C0' to 'C4') are required that set safety requirements for different types of drones [40]. With the exceptions of privately built drones for personal use and drones purchased before January 2024, all drone operations in the 'open' category will require a drone bearing a class identification label. It is expected that drones bearing class identification labels will become available commercially by the end of 2022. A drone with class identification label 'C4' in subcategory 'A3' has an allowed maximum weight of 25 kg and may fly over uninvolved people even if this should be avoided when possible.

Even if a drone with class identification label 'C4' in the subcategory 'A3' may be used for automatic operations, the 'open' category requires that the remote pilot can take control of the drone to intervene in unforeseen events for which the drone has not been programmed. If an autonomous drone should conduct flights without the intervention of a pilot, it would most likely be performed within the 'specific' category, which is targeted for riskier operations not covered under the 'open' category.

To operate in the 'specific' category, it will be possible to conduct flights following European *Standard Scenarios* (STS) according to regulations applicable from 1st of January 2024. Two STS have been defined so far, however, both of them require a remote pilot. Therefore, STS are currently not applicable to autonomous operations and the drone operator needs to apply for operational authorization from the National Aviation Authority (NAA) in the country where the operator is registered. If obtained, an operational authorization provides flexibility and can respect the various requirements of different kinds of operations. Two alternative approaches exist for applying for operational authorization:

- Predefined Risk Assessment (PDRA)
- Specific Operations Risk Assessment (SORA)

If the intended operation is covered by one of the published PDRAs, conducting a 'full' risk assessment is not required. Instead, following the instructions of the PDRA and preparing required documentation forms the base of the application which is to be submitted to the NAA.

PDRAs are published by European Union Aviation Safety Agency (EASA), as "Acceptable Means of Compliance and Guidance Material" to EU Regulation 2019/947 [41]. All published PDRAs so far require a remote pilot, however. Therefore, a SORA needs to be performed for the level of autonomy that is required for our targeted use cases (described in Chapter 4).

The terms for the operational authorization are based, e.g., on the following information that is to be included in the SORA:

- Operational description – type of flights and how they are to be performed
- Flight area – over which area are the flights to be performed?
- Airspace – in which airspace are the flights to be performed?
- Operational limitations – which are the limitations of the flights?
- Drone – which drone system or systems are to be used?
- Organization – including a description of the operator's competence

While several EU projects work towards SORAs for autonomous drones, only SORAs for pilot-controlled drones are known to us. Besides drone categories, geographical zones can pose additional restrictions to drone flights.

8.2.1.2 Geographical zones

Geographical zones can restrict flight operations independent of the category in which the flight is conducted (including the 'open' category or flights according to STS) [29]. If a flight should be conducted in an area that is covered by a geographical zone, flight authorization is needed from the authority in charge of it. An example is given on the EASA website [42]: "if the operator has a contract to clean the windows of a prison protected by a geographical zone, they may need the flight authorization from the authority in charge of the prison".

EU member states can decide to designate cross-border geographical zones. Geographical zones and all other regulations described within this section (Section 8.2.1) apply to the EU airspace only, however. This includes the airspace over territorial waters which extend up to 12 nautical miles (22 224 m) from the shore. Beyond that, different regulations will apply to the airspace over international waters.

8.2.2 EU Regulations – Marine Equipment Directive

The operation of the drone system onboard a ship is discussed in the following, where the Marine Equipment Directive (MED), Directive 2014/90/EU [38] sets out performance and testing standards to be met by marine equipment placed on board an EU ship.

Regulation (EU) 2022/1157 amending the MED specifies design, construction and performance requirements as well as testing standards for marine equipment. Chapter 3 of the regulations covers fire protection equipment and specifies the applicable regulations of SOLAS [3] and the International Maritime Organization (IMO) in MED/3.51a "Fixed fire detection and fire alarm systems components for control stations, service spaces, accommodation spaces, cabin balconies, machinery spaces and unattended machinery spaces: — control and indicating equipment". Additionally, testing standards and modules for conformity assessment are given.

8.2.3 International Regulations – The International Code for Fire Safety Systems

SOLAS specifies safety standards for the design and operation of ships, as well as for specific equipment intended for use onboard ships. The FSS Code [39] provides international standards for the fire safety systems and equipment required by SOLAS.

Chapter II-2 "Construction – Fire Protection, Fire Detection and Fire Extinction" of SOLAS entered into force on 1st of July 2002. It sets regulations with the aim of preventing fires through materials that reduce fire risks, detecting fires rapidly as well as containing and extinguishing them. Further, ships shall be designed to enable easy evacuation of crew and passengers.

The FSS Code provides international standards of the engineering specifications for fire safety systems that are required by SOLAS Chapter II-2. The FSS Code is mandatory since 1st of July 2002. FSS-Code Chapter 9 details the specification of fixed fire detection and fire alarm systems, e.g.:

> "Any required fixed fire detection and fire alarm system with manually operated call points shall be capable of immediate operation at all times (this does not require a backup control panel). Notwithstanding this, particular spaces may be disconnected, for example, workshops during hot work and ro-ro spaces during on and off-loading." (FSS Code 2.1.1).

The *fire detection system* is supposed to control and monitor input signals from fire and smoke detectors and manual call points only. For the drone system to be able to communicate directly with the fire detection system it, therefore, needs to be regarded as a fire detector giving input signals to the system. Alternatively, the drone may be regarded as an "other fire safety system" in which case it can receive input signals from the fire detection system but not to provide any outputs to it. In any case, two-way communication is not allowed. If the drone is supposed to be connected to the fire detection system, the drone would always be required to comply with any regulations relating to fire detection equipment. This might not be possible because this type of equipment has not been considered in the relevant standards and regulations

Alternatively, the drone could be connected to a *decision management system*, which in turn may communicate with the fire detection system, instead of connecting to the fire detection system directly. This is not to be confused with but related to the *decision support system* which is used for emergency management and mandatory to be provided on the navigation bridge according to SOLAS. All foreseeable emergency situations need to be covered by the emergency plan that the decision support system provides, a list of emergencies (including fire) is specified by SOLAS. The following rules apply for fire detection systems connected to a decision management system:

1. the decision management system is proven to be compatible with the fire detection system;
2. the decision management system can be disconnected without losing any of the functions required by this chapter for the fire detection system; and
3. any malfunction of the interfaced and connected equipment should not propagate under any circumstance to the fire detection system (FSS-Code 2.1.3).

Further, EU Regulation 2021/1158 [43] states in Article 1 that design, construction and performance requirements as well as testing standards apply to marine equipment listed in the Annex of EU Regulation 2021/1158. If the drone were considered to be, e.g., a part of the decision management system or a standalone monitoring system (which are not listed in the Annex) the requirements stated by the MED would not be applicable. This would considerably simplify the deployment. Thus, connecting the drone to a decision management system or deploying it as a standalone monitoring system appears to be feasible within applicable regulations. This means that the drone system would be deployed as a complement to existing safety systems and cannot replace any.

8.2.4 Conclusions on Legal Feasibility

The use of the drone system onboard a ship is regulated in terms of the used EU airspace and the maritime context. Applying for operational authorization in the EU airspace means that a SORA needs to be performed, which requires that, e.g., operational description and limitations as well as drone specifications, flight area and operator organisation are determined. Thus, applying for operational authorization will not be possible unless all details regarding the use of the drone are clarified and decided. Seeking a partnership with a ship operator and a ship classification society would be a way to move forward regarding the practical use of a drone on a ship, and further investigations of any regulations for the intended use cases.

The international maritime safety conventions require that the equipment carried on board ships complies with certain safety requirements regarding design, construction and performance. Detailed performance and testing standards for certain types of marine equipment have been developed by IMO and by the international and European standardisation bodies.

For a drone system to be compliant with international testing standards (e.g., fire alarm system components) through conformity assessment procedures might not be possible. The reason is that this type of equipment simply has not been considered in the MED and relevant standards and regulations. This means that attribution of the Wheel Mark to the drone, i.e., the mark of conformity according to the MED, would require an amendment of the existing regulations. This is only required, however, if the drone should become part of the fixed alarm system on board EU ships, or in some way considered part of the maritime equipment regulated under MED. Instead, seeing the drone system as complementary and connecting it to a decision management system or deploying it as a standalone monitoring system appears to be feasible within applicable regulations.

In summary, deploying the drone system on a ship within the EU airspace seems feasible but performing the required SORA and obtaining operational authorization can be challenging and time-consuming. To move forward effectively, we recommend performing these steps in tight cooperation with a ship owner as well as a ship classification society.

9 Assessment of Usefulness

The usefulness of the drone system is assessed using the results from an inline questionnaire that we designed for this purpose and sent to LASH FIRE partners, the Swedish Maritime Administration and maritime experts within RISE (incl. SSPA Sweden). The participants partly represented the potential customers and partly potential providers of such a system.

Figure 25 Questionnaire title image

The questionnaire presented video material gathered during the tests and demonstration described in Chapter 7. Three videos introducing the different use cases were presented (title image shown in Figure 25):

- Intro / Fire Patrol: https://youtu.be/ZsLoR8QqYMc
- Fire Resource Management: https://youtu.be/wPCA_L4ZX0E
- Search & Rescue: https://youtu.be/l1fvPJmlSQI

Figure 26 Prototype user interface (Control Tower) shown during the questionnaire

Further, the prototype user interface of the ground station was presented (see Figure 26, the ground station software Control Tower is presented in Section 6.3.2.2 and 8.1.1). A copy of the full questionnaire can be found online[28]. All questions and possible answers are described together with the results in the following. A total of 34 persons answered the questionnaire. The next section focuses on the participants' backgrounds.

9.1 About you

The questionnaire's first section asked questions about the recipients' backgrounds. The age of the participants was collected in 10-year buckets (e.g., 35 to 44). All participants were between 25 and 64 years old. Half of the participants were 45 to 55 years old, the other half was almost evenly distributed older or younger.

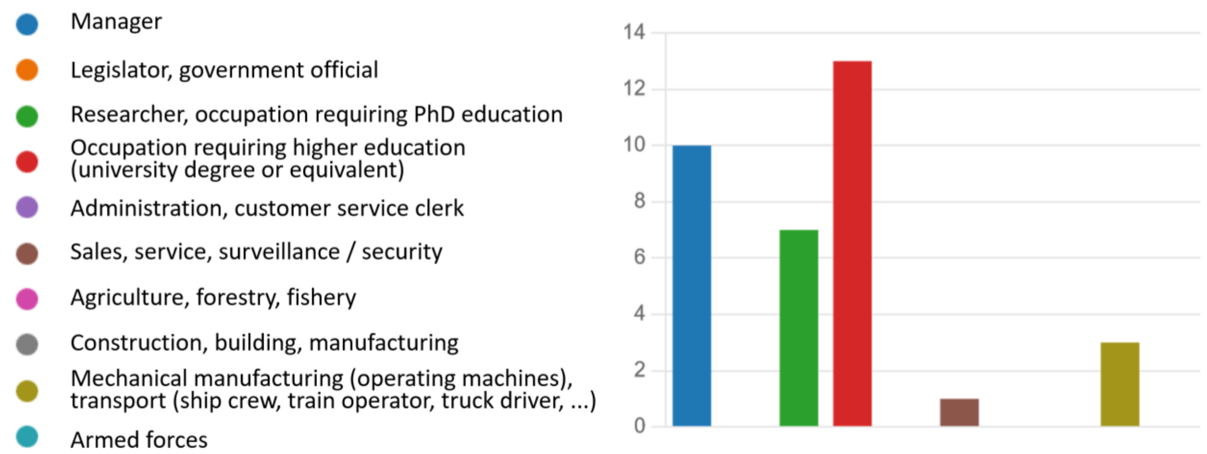

Figure 27 Question 2: "To which group does your occupation mainly belong to?" (Based on the Swedish Standard Classification of Occupations 2012)

Most of the participants were either managers (approx. 29%), researchers (approx. 21%) or had another occupation requiring higher education (approx. 38%). More details are given in Figure 27. The participants' occupations were mainly within a maritime profession (approx. 56%), either off board (approx. 32% of total) or on board (approx. 24% of total), more details are given in Figure 28.

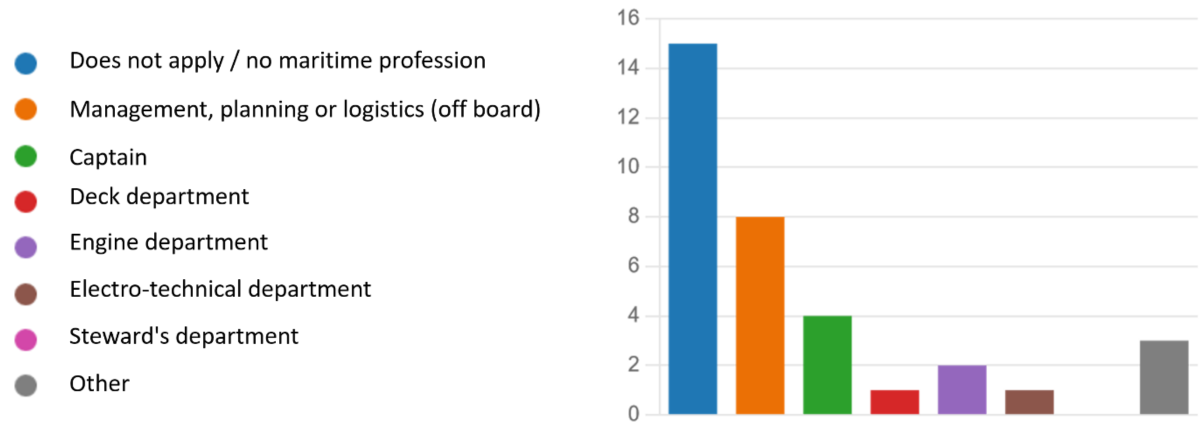

Figure 28 Question 3: "Where is your main maritime profession located?"

The majority of participants worked for universities and research institutes (approx. 44%), or shipping companies (approx. 32%). The remaining participants worked for consulting firms (approx. 12%),

[28] https://forms.office.com/r/e9gSAGA3m9

technology suppliers, ship design / construction companies, or governmental shipping agencies / associations (one or two participants each, where no percentage is given).

Only a few of the participants reported having expert knowledge in the general field of drones (approx. 12%), and all of them reported having expert knowledge in seafaring as well. In general, more than half (approx. 53%) of all participants reported having expert knowledge in seafaring.

9.2 Use Case 1 (of 3): Fire Patrol

This section of the questionnaire first gave a high-level description of the fire patrol use case (see Section 4.1 for details) and the potential automation thereof:

> Fire patrols, also called fire rounds, are usually carried out by the crew, where one or more crew members walk around the ship at regular intervals with the aim of detecting potential fires (referred to as manual fire patrol).
>
> Automated fire patrols could be realized using an autonomous drone that flies a predefined route at regular intervals and tries to sense high temperatures using a state-of-the-art thermal camera. Only in case of irregularities, the crew is warned and needs to review the images from the camera (both thermal and regular visual) to decide whether to act on the warning or ignore it.

The description was followed by a video, giving an impression of how the system might look like when used on ship[29]. The questions were provided as two sets of statements, where participants were asked to provide their response to each statement on a Likert scale [44] with the following options: ‘Strongly disagree’, ‘Disagree’, ‘Neutral’, ‘Agree’, ‘Strongly agree’. The statements were first focused on manual fire patrols (see Figure 29), trying to assess the current state, followed by statements on automated fire patrols in general (where a drone system would be one option for atomisation, see Figure 31). Participants were further encouraged to provide additional comments explaining their replies or providing additional information.

9.2.1 Manual Fire Patrols

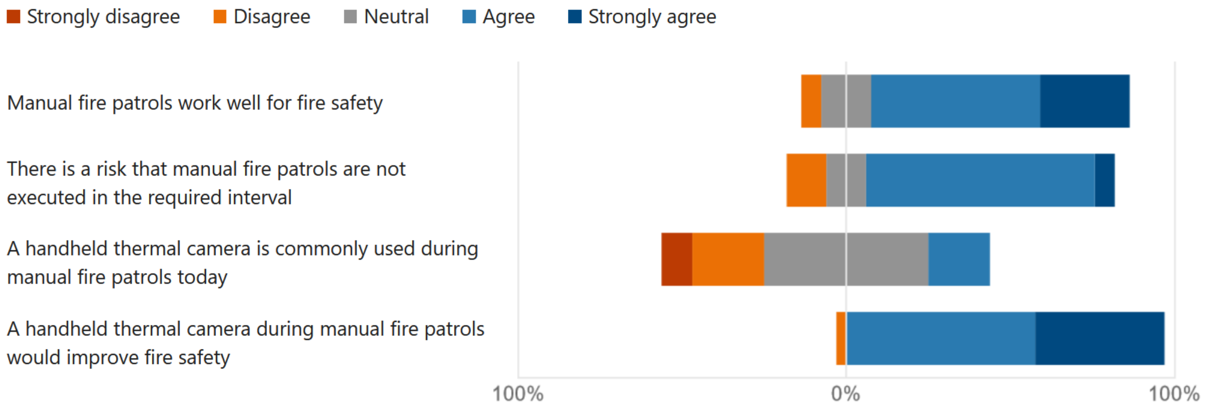

Figure 29 Question 6: "How do you judge the following statements about manual fire patrols?"

Even though approx. 79% of participants either agree or strongly agree that manual fire patrols work well for safety, approx. 76% also agree or strongly agree that there is a risk that manual fire patrols are not executed in the required interval (details in Figure 29). Virtually all participants (approx. 97%) agree or strongly agree that a handheld camera as shown in Figure 30 would improve manual fire patrols. Only few participants (19%) agreed that a handheld thermal camera is commonly used

[29] https://youtu.be/ZsLoR8QqYMc

during manual fire patrols already today, while approx. 32% strongly disagree or disagree. Half of the participants were unsure about this statement and gave a neutral response.

Figure 30 An example of a handheld thermal camera that could be used during manual fire patrols (source: FLIR.com)

Half of the participants left further comments, highlighting that how fire patrols are executed varies greatly in the industry. According to some comments, fire patrols are commonly combined safety rounds, where not only fire risks but also safety risks like obstructed doors, shifted cargo or potential leakage are checked. In cases where thermal cameras are used during manual fire rounds, some comment that they are not commonly used but only to check a suspicious area or anomaly. Additional risks to manual fire patrols are also mentioned, where fire patrols might be executed according to schedule but with insufficient coverage due to an unsuitable route or complacency.

9.2.2 Automated fire patrols

Automated fire patrol would improve fire safety on the weather deck according to the majority of participants (71% either agree or strongly agree, see Figure 31 for details). Whether automated fire patrols would relieve the crew was rated with a more mixed result, though, 56% of participants rated the statement positively and 32% negatively (either strongly disagree or disagree). The vast majority of participants (88% agree or strongly agree) can see automated fire patrols as a complement to manual fire patrols. Much lower is the confidence in the possibility of automated fire patrols replacing manual fire patrols with 59% rating this statement negatively and approx. 27% of participants even disagreeing strongly.

The majority of participants did not think that manual fire rounds with a handheld thermal camera (as shown in Figure 30) would work equally well as automated fire rounds with a drone (approx. 41% strongly disagree or disagree), but a considerable share of participants (approx. 38%) rated this statement neutral. Approx. 21% could even see drone-based fire patrols and manual fire patrols with a thermal camera performing equally well.

False warnings, i.e., the automatic system signalling a potential fire even if there is none, have a considerable impact on the perceived usefulness of the system according to the participants. More than half of the participants disagree that the usefulness of automatic fire patrols would be limited with false warnings occurring once a month (59%). If false warnings would occur once a day instead, the result is almost inverted with (50%) agreeing that this would limit the usefulness of the automatic fire patrols. For all three questions on false warnings, a considerable number of participants rated the statements neutrally (approx. 24%, approx. 27%, approx. 32% for false warnings occurring daily, weekly or monthly, respectively). One reason for this might be that we did not explain in detail what false warnings would mean exactly and, therefore, some participants might have been unsure of the impact.

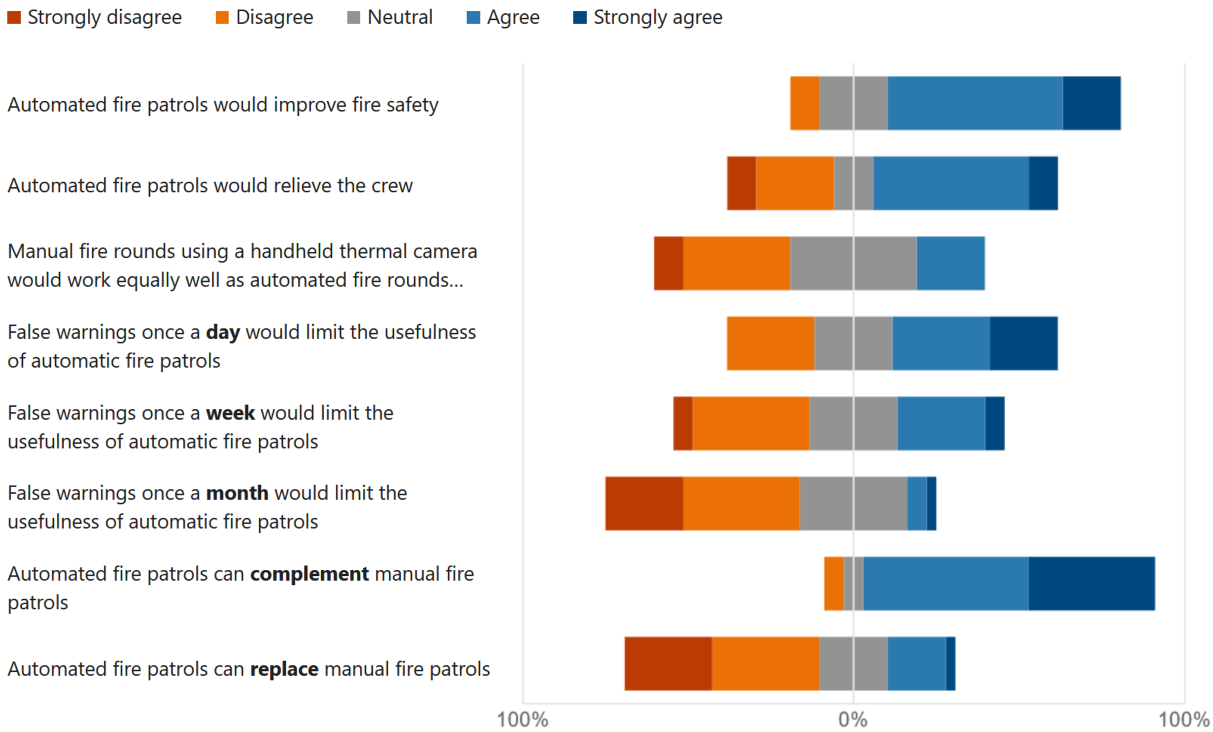

Figure 31 Question 8: "How do you judge the following statements about automated fire patrols in general?"

Further comments were provided by 14 participants. Some stressed that automated fire patrols would be a complement and not a replacement because it is seen as important to keep human intelligence in the loop and maintain direct communication between the crew member performing the fire patrol and the rest of the crew (including getting specific instructions). At the same time, automation is seen to avoid human errors and, even though technology might not be mature enough to replace humans today, technology is seen as constantly improving.

9.3 Use Case 2 (of 3): Fire Resource Management

The section on the fire resource management use case (see Section 4.2 for details) followed a similar pattern as the previous section on the fire patrol use case. First, a high-level textual and video introduction was given, followed by two sets of statements to be rated on a Likert scale. The first set focused generally on managing active fire situations using information from video surveillance (see Figure 32), and the second on controlling the drone system in such a situation (see Figure 33).

While the video introduction can be found online[30], the textual introduction was as follows:

> In case of an active fire, allocation of resources is critical to achieve as efficient containment of the fire as possible while maintaining general safety as well as potentially performing and managing evacuation. At the same time, it is challenging to get and maintain an overview of the situation.
>
> While video surveillance (also called closed-circuit television, CCTV) in the form of fixed thermal and visible imaging cameras might virtually cover the whole weather

[30] https://youtu.be/wPCA_L4ZX0E

deck on modern ships, the bird's-eye perspective provided by a drone-mounted thermal camera could provide a more directed overview over critical situations.

9.3.1 Video Surveillance

Generally, video surveillance on ship was rated quite positively (see Figure 32). Approx. 74% of the participants agreed or strongly agreed that video surveillance is crucial to get an overview of an active situation, with only approx. 9% disagreeing. The availability of a bird's-eye view would enable understanding the situation faster according to approx. 88% of the participants and reduce stress in managing the situation according to approx. 65% of the participants (agree or strongly agree summarized for both values). The majority of participants see room for improvement, though, as approx. 47% strongly disagree or disagree with the statement that video surveillance is sufficient on modern ships and approx. 47% rated this statement as neutral. A considerable number of participants think that a human needs to confirm a fire and that video surveillance is not sufficient (approx. 18% agree), while 44% strongly disagree or disagree with this statement.

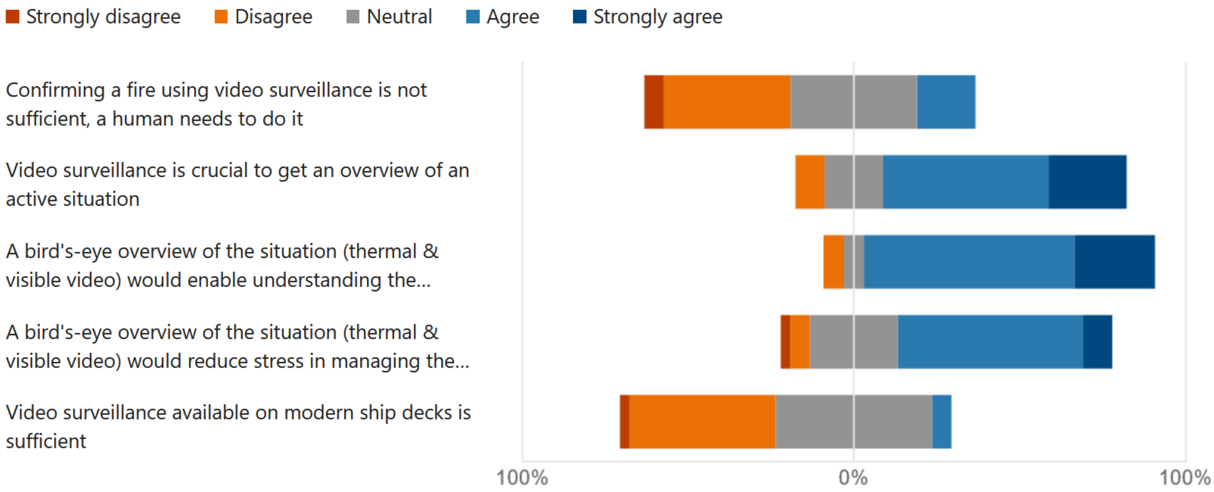

Figure 32 Question 10: *"How do you judge the following statements about managing resources (personnel and countermeasures) in an active fire situation on deck?"*

Thirteen participants left further comments. A general theme concerning the drone system is that it would be a tool that can be safely operated by the crew and enable a quick overview that can improve the chances of "winning the battle", however, influences of strong weather (on video quality and the possibility to fly at all) as well as usefulness when fires often originate from closed decks are a concern. Concerning fixed video surveillance, some comments state that cameras usually do not cover everything, and that smoke is an issue that can block the view, especially on closed decks.

9.3.2 Control of the Drone System

Regarding the control of the drone system in an active situation (see Figure 33), it was seen as crucial that the drone does not require human interaction by most of the participants (approx. 62% agreeing or strongly agreeing). Providing the possibility for controlling the drone through a simple touch interface for changing the provided perspective was seen positively by approx. 79% of the participants (agreeing or strongly agreeing). Half of the participants did not see interacting with the touchscreen as a distraction (strongly disagreeing or disagreeing) while approx. 21% did (agreeing or strongly agreeing). The same number of participants saw the drone system in general as a distraction, but fewer participants explicitly stated that the drone system is not a distraction (approx. 41% strongly disagreeing or disagreeing and approx. 38% neutral compared to approx. 29% when asked about the touchscreen).

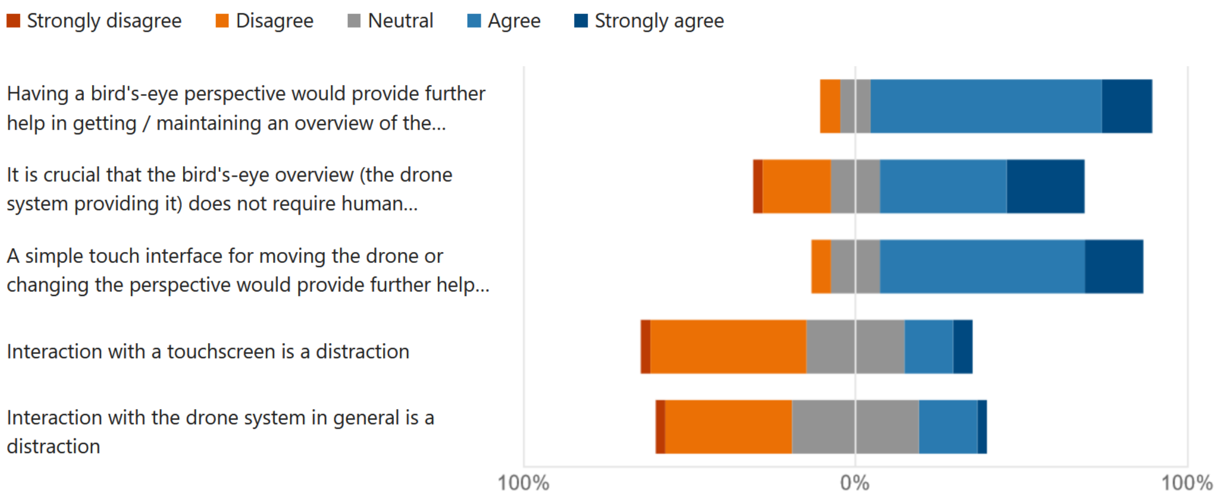

Figure 33 Question 12: "How do you judge the following statements about controlling the drone system during an active situation?"

Twelve participants left comments, some of which describe in some detail that it is not easy to answer the question generically for every kind of situation or vessel type. Generally, the possibility to manipulate the drone's view is seen as very helpful when the crew is well-trained and used to the drone system. There are some concerns that the drone system will either distract or be seen as a toy when the crew is not accustomed to the drone system.

9.4 Use Case 3 (of 3): Search & Rescue

The same pattern used in the previous two sections of the questionnaire focusing on the fire patrol and fire resource management use cases, respectively, was also used for the section on the final use case of search & rescue missions (see Section 4.3 for details). The introductory video can be found online[31], the textual introduction was as follows:

> Man overboard incidents happen regularly, but search and rescue missions are in the majority of cases unsuccessful. The main problem is the time it takes to initiate the search and rescue mission: An average person will become unconscious in 5 °C cold water in under 15 minutes. This duration, however, is generally required to turn the ship back towards the point where the person is suspected to have gone overboard.
>
> A drone could support search and rescue missions by flying directly to the point where the person is suspected to have gone overboard and search the area with the thermal camera. The aim would be to speed up the search of the missing person and enable a timelier launch of a rescue boat.

9.4.1 Current State of Search and Rescue Missions without Drones

The first set of statements focused on the current state of search & rescue missions (see Figure 34), where 59% of participants did not think that man overboard incidents are usually detected immediately, approx. 38% replied neutral. Turning the ship during such an incident was seen as slightly more positive, as 23% of participants thought it works well (agree or strongly agree) and 45% thought it does not (strongly disagree or disagree). 90% of the participants either agreed or strongly agreed with the statement that searching for the missing person needs to be improved and no

[31] https://youtu.be/l1fvPJmlSQI

participant disagreed. Further, approx. 61% agreed or strongly agreed that rescuing the located person needs to be improved, with approx. 7% disagreeing and 32% replying neutral.

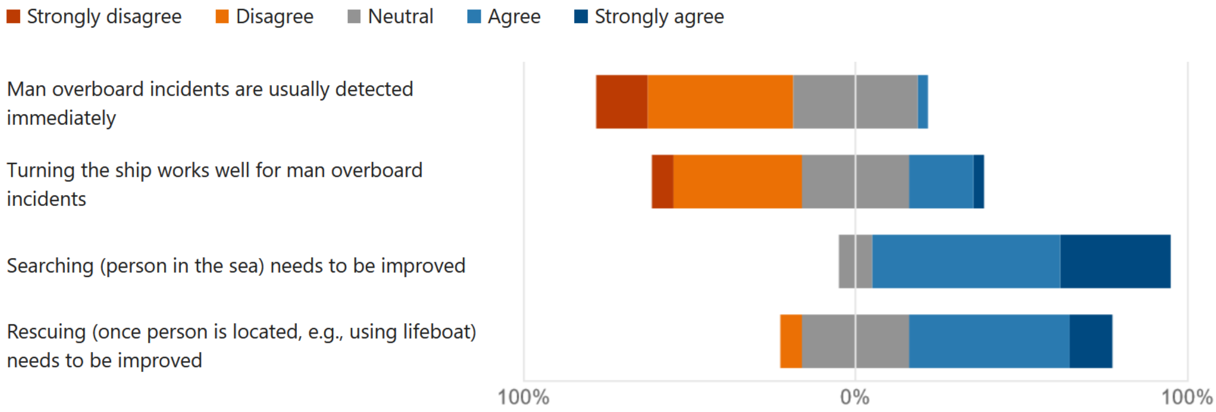

Figure 34 Question 14: "How do you judge the following statements about the current state of search and rescue missions (without drones)?"

Additional comments were provided by 14 participants, most stressing the difficulty of locating a missing person in the sea, describing the various circumstances (weather influences like rain or fog, and different daytimes) and stressing the need for improvements using modern technology.

9.4.2 Use of a Drone System for Search and Rescue Missions

The second set of statements focused on the use of a drone for improving the current state (see Figure 35), where the use of a drone for search & rescue missions was largely seen as positive and 88% of the participants saw a drone to be suitable technology for this use case (agree or strongly agree) and no participant saw drones as unsuitable. Approx. 81% replied neutrally to the statement that more suitable technology than drones exists and approx. 10% each either agreed or disagreed. The provided comments from participants disagreeing suggested that the drone can be complemented with other technology, e.g., enabling the drone to drop a life vest or including location devices and accelerators that could detect a fall from height in the crew members' equipment. All three statements of "A drone could reduce the time to locate the person in sea", "A drone could help the person in sea feel secure until rescued" and "The drone should carry support, e.g., inflatable life vest" were rated positively by more than 76% of the participants (agreeing or strongly agreeing). Only the statement suggesting that a drone would help the missing person feel secure until rescued received negative ratings, where 3% of participants disagreed.

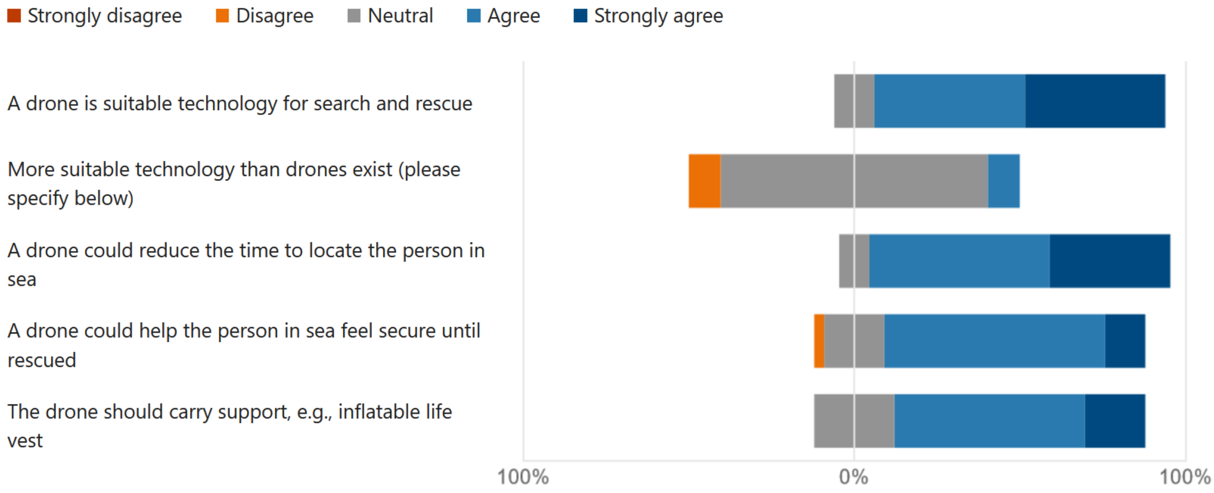

Figure 35 Question 16: "How do you judge the following statements about the use of a drone in search and rescue missions?"

Further comments were provided suggesting man overboard incidents are more likely to happen under strong winds that might make the use of the drone difficult. At the same time, the drone would be a comfort to the missing person if unable to call for help, because the presence of the drone would signal that the situation is understood by the crew on ship.

9.5 General Questions on Use of Autonomous Drones on Deck

After introducing the drone system as well as three potential use cases, the final section asked more general questions comparing the different use cases and rating the drone system itself. This section did not follow the previous pattern of two sets of statements to be rated on a Likert scale but used a mix of different question types. No further introductory text or video was given.

Figure 36 Question 18: "Which is the most promising use case (top ranking = most promising)?"

As shown in Figure 36, 75% of participants selected search & rescue as the most promising use case, fire patrol was chosen first by approx. 18% and fire resource management by approx. 6%. Fire patrol and fire resource management were almost equally often ranked as the second choice (approx. 44% and approx. 41%, respectively). Further potential use cases that are mentioned in comments are checking whether cargo has shifted during strong weather and observation of evacuation situations.

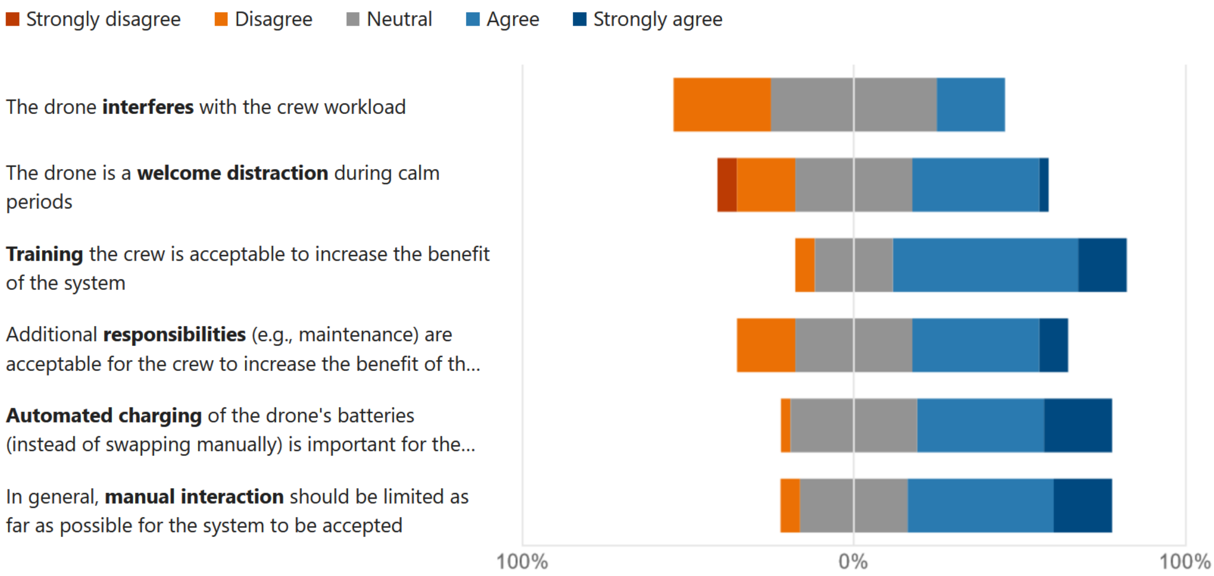

Figure 37 Question 20: "How would you judge the following statements on time allocation for a drone system?"

Further statements regarding time allocation for the drone system were presented to be ranked with the same Likert scale used in the previous section, see Figure 37. Approx. 30% agreed that the system would interfere with the crew's workload, while approx. 21% disagreed. Half of the participants rated this statement neutral, some commenting that they do not have enough experience to judge. The potential of the drone being a welcome distraction was rated more positively, with approx. 41% agreeing or strongly agreeing but approx. 24% strongly disagreeing or disagreeing. A strong majority of participants rated training as acceptable for the crew to increase the benefit of the system, with approx. 71% agreeing or strongly agreeing and 6% disagreeing. Additional responsibilities for the crew were seen as more negative but still positive by the majority of participants, with approx. 18% disagreeing and approx. 47% agreeing or strongly agreeing.

The last two statements on time allocation focused on the manual interaction required by the drone system. Approx. 62% of the participants agreed or strongly agreed that manual interaction should be limited as far as possible in order for the system to be accepted and approx. 6% disagreed. Similarly, automated charging, e.g., using a drone docking stating described in Section 5.1, instead of manually swapping batteries was seen as important by approx. 59% of participants (agreeing or strongly agreeing), while approx. 3% disagreed with this statement.

Participants were further asked about factors that influence trust in the drone system as follows:

> *In order to be able to trust the drone system, it needs to be reliable even under adverse conditions, e.g., weather or active fire. Can you think of other factors influencing trust in the system?*

Eighteen participants provided comments on this question. Frequently mentioned was the absence of false alarms, resistance to adverse weather, a high degree of automation and high ease of use. It was further mentioned that the crew's acceptance is key, e.g., by giving ownership of the adoption process, and that cybersecurity needs to be on a high level to maintain the confidentiality of communicated data and robustness of the overall system.

The following ranking questions targeted the same ten technical challenges in two different ways (see Figure 38 and Figure 39). First, the perceived importance of solving a specific challenge should be ranked, then the difficulty to do so. Two participants abstained from ranking importance, eleven abstained from ranking difficulty. Some commented that they did not feel confident about ranking the options based on their expertise.

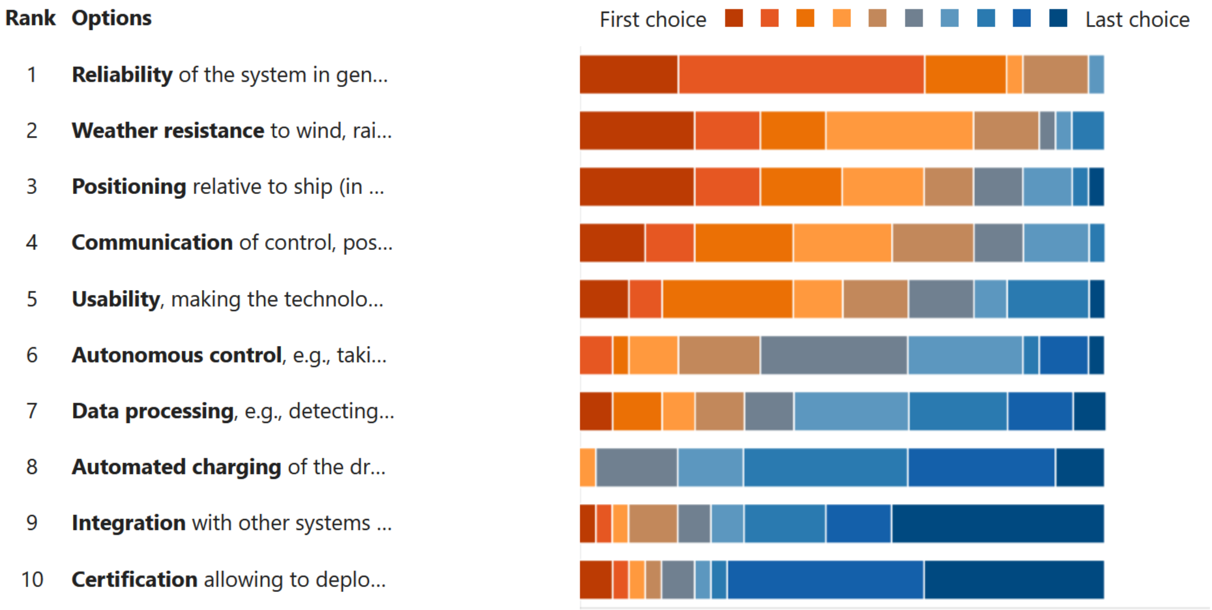

Figure 38 Question 23: “How would you rank the importance of solving the following technical challenges or concerns (top ranking = most important to be solved)?”

Figure 38 gives a summary of how the 32 participants of this question ranked the importance of the mentioned individual technical challenges and the resulting ranking. Especially when looking at the last five items in the resulting ranking, it seems to have a bias towards the original ranking the items were presented in the question, which was:

1. **Positioning** relative to ship (in order to follow paths autonomously)
2. **Communication** of control, position, and sensor / video data between ship and drone
3. **Reliability** of the system in general
4. **Weather resistance** to wind, rain, snow, heat, cold, salt, ...
5. **Usability**, making the technology usable by non-experts
6. **Autonomous control**, e.g., taking off and landing from the moving ship
7. **Data processing**, e.g., detecting fire threats in thermal / visual video
8. **Automated charging** of the drone's batteries (instead of manual charging)
9. **Certification** allowing to deploy the system within international regulations
10. **Integration** with other systems on ship

Unfortunately, the tool in which we created the questionnaire in (Microsoft Forms) did not allow the original ranking to be randomized, which might have helped in removing the bias. Even when ranking after the percentage of participants ranking a certain item as most important, however, the top five items remain almost stable (reliability moves from 1st to 3rd):

1. **Weather resistance**, first choice for approx. 22%
2. **Positioning**, first choice for approx. 22%
3. **Reliability**, first choice for approx. 19%
4. **Communication**, first choice for approx. 13%
5. **Usability**, first choice for approx. 10%

It can also be noted that Certification and Integration were ranked first in importance by approx. 6% and approx. 3% of participants who answered the question, respectively, despite landing on the last to spots in the averaged ranking.

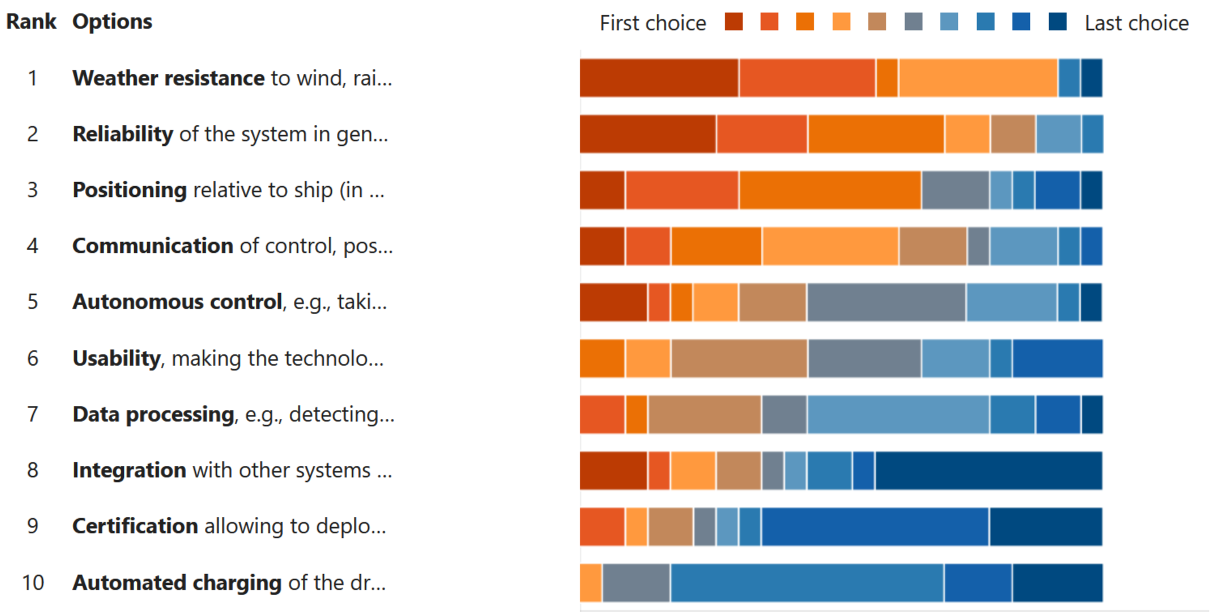

Figure 39 Question 24: "How would you rank the difficulty of the following technical challenges or concerns (top ranking = most challenging)?"

Figure 39 gives a summary of how the 23 participants of this question ranked the difficulty of the mentioned individual technical challenges and the resulting ranking. The comments that we made about the ranked importance of technical issues having a bias towards the original ranking, especially for the last five challenges apply even here. When ranking the first five challenges according to the number of participants ranking a certain issue as most difficult (and using 2nd and 3rd choice as tie-breakers), the following ranking is obtained:

1. **Weather resistance**, first choice for approx. 30%
2. **Reliability**, first choice for approx. 26%
3. **Autonomous control**, first choice for approx. 13%
4. **Integration**, first choice for approx. 13%
5. **Positioning**, first choice for approx. 9%

While Weather resistance, Reliability, Autonomous control and Positioning remain fairly stable when comparing this ranking to the averaged ranking result of Figure 39, Integration is highlighted to be perceived as the most difficult challenge by a considerable number of participants.

The second but last question focused on rating several similar statements on expenditures for the drone system. 31 participants answered this question, 3 abstained and some commented that they do not know the current price ranges for this kind of technology or that they are unable to estimate the money value of the risk reductions provided by it. Consequently, more than one third of the ratings were 'neutral' for all statements. Most of the statements to be rated stated different values of investment for the drone system:

- Investing **25.000€** seemed reasonable for approx. 55% of participants (agreeing or strongly), unreasonable for 3% (disagreeing)
- Investing **50.000€** seemed reasonable for approx. 33% of participants (agreeing or strongly), unreasonable for 20% (strongly disagreeing or disagreeing)
- Investing **100.000€** seemed reasonable for approx. 13% of participants (agreeing or strongly), unreasonable for 47% (strongly disagreeing or disagreeing)

- Investing **200.000€** seemed reasonable for approx. 3% of participants (agreeing or strongly), unreasonable for 60% (most strongly disagreeing with 47%, rest disagreeing)

Approx. 45% of the participants agreed (agreeing or strongly agreeing) that it is more important to keep operational expenditures low than keeping the initial investment costs low. Approx. 17% disagreed with this statement.

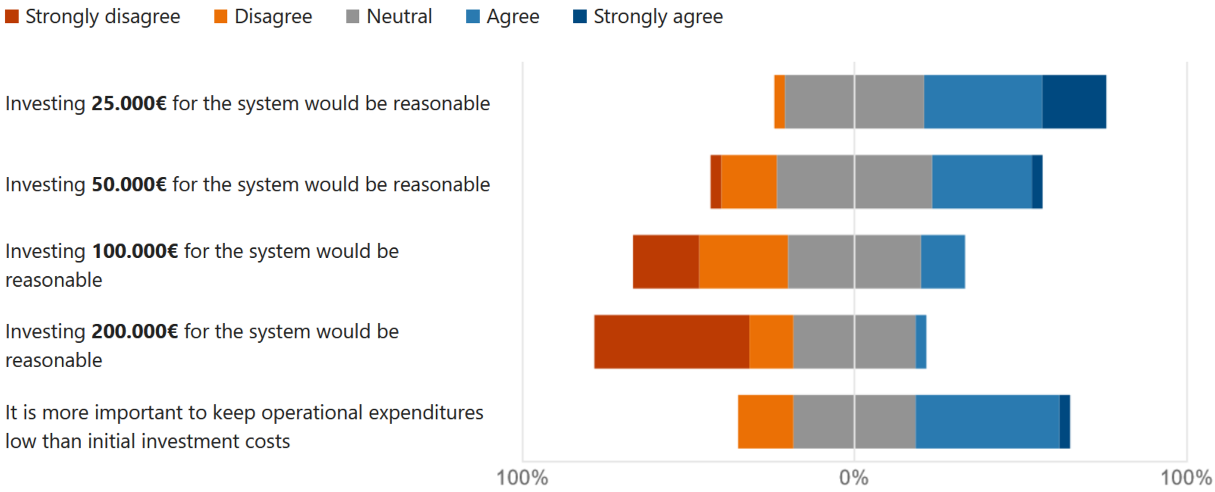

Figure 40 Question 26: "How do you judge the following statements about expenditures for the drone system?"

Some participants provided comments that highlight the difficulty of estimating a reasonable cost for the system. Generally, a clear benefit would need to be demonstrated and still it might be difficult to convince ship operators to invest if the drone system is not required to fulfil regulations due to the risks it introduces.

Finally, the participants were asked to rate the likeliness of drones playing a role in improving safety on ship within the next 5 to 10 years on a scale of 1 to 10. The result is shown in Figure 41. On average, the likeliness was rated at 6.97.

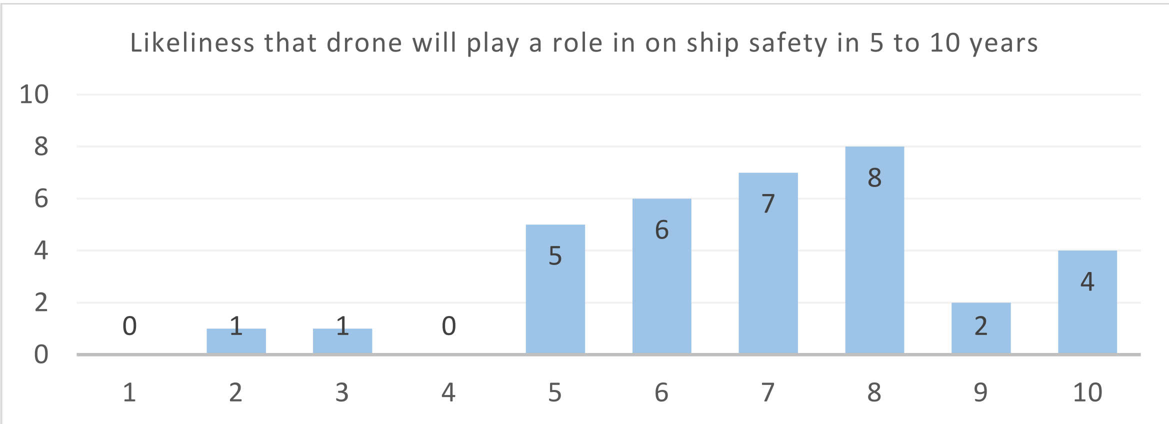

Figure 41 Question 28: "How likely do you think it is that drones will play a role in improving safety on ship within the next 5 to 10 years?" Result as absolute counts

Figure 42 shows the "Net Promoter Score" [45], which is a market research tool that tries to estimate business growth as a result of customer experience. It is calculated by grouping the received ratings into 'Detractors' (rating 1 to 6), 'Passives' (rating 7 to 8) and 'Promoters' (rating 9 to 10). The percentage of Detractors is then subtracted from the percentage of Promoters. Usually, the result is compared to competitors, but in our case, there are no obvious competitors. The results of -20% on its own suggests that when only relying on the impression of the drone system on the participants of this questionnaire, the "business" of drone systems for improving safety on ship as presented would not grow, because there are too few people promoting their use and too many having a sceptical or negative opinion.

Promoters	6
Passives	15
Detractors	13

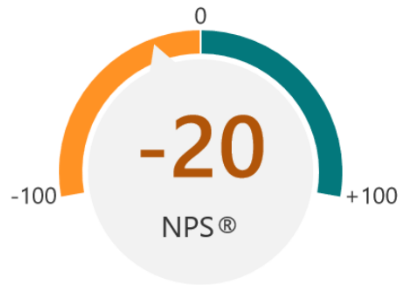

Figure 42 Question 28: "How likely do you think it is that drones will play a role in improving safety on ship within the next 5 to 10 years?" Result as Net Promoter Score (NPS)

This concludes the summary of the questionnaire results. In the following, the major outcomes of the questionnaire are discussed.

9.6 Discussion of Main Outcomes of the Questionnaire

The questionnaire results neither show exaggerated expectations nor strong aversions towards the drone system. Overall, the outcomes are in line with our own experiences and project-internal discussions that we had while designing the system and preparing the feasibility analysis. In a few sentences, we would summarize the main outcomes for each of the use cases as follows:

1. **Fire patrols:** Automated fire patrols using the drone system can complement manual fire patrols and improve fire safety, even when a handheld thermal camera is used during manual patrols. It is important, however, to keep false warnings of irregularities at a minimum (once a day or fewer). Further technological advances and trust in the system are required to replace manual fire patrols.
2. **Fire resource management:** Video surveillance available today should be further improved, the bird's-eye view provided by the drone system would enable faster understanding of active situations and reduce stress in managing them. While manipulating the view provided by the drone is seen as very helpful, it is crucial that the *required* interaction with the drone is kept at a minimum.
3. **Search and rescue:** Even if this use case was not the focus of this work, this use case is seen as the most promising for the drone system to improve, because there is a strong need for improving the localisation of missing persons at sea. Further, the drone system is seen as a suitable technology to reduce the time until the person is located, help the missing person feel secure until rescued and potentially carry support in the form of an inflatable life vest.

Generally, it is seen as possible to integrate the drone system within the crew's workload when appropriate training is provided that makes and keeps the crew familiar with the system. Training is seen as crucial to avoid distractions and maximize the benefits. Throughout the questionnaire, adverse weather conditions are mentioned as a major concern that might limit the use of the system, often in situations where it would be needed most. Considering that multicopters like the design presented in Section 6.2.1 are quite robust and extendable, and that multirotor-based certified aircraft exist [46], we see this more as a cost issue than a technical one. It is most-certainly possible to build a drone that can take off in all reasonably thinkable weather conditions, but it might be very expensive. A major challenge in bringing such a drone system to the market is guaranteeing clear benefits under specified conditions at a reasonable selling price.

The achievable selling price for the fully certified and integrated system with automated charging is hard to estimate because integration and certification (see Section 8.2) could become a driving factor for the final price (see Section 6.5). According to the questionnaire's participants, the price tag should remain under 50.000 € which can be reasonable at a certain volume, e.g., a deal with a ship operator to equip 10+ ships with the same system.

A further major challenge is that the ship operator and crew need to feel confident in the system and trust it to provide benefits during stressful situations. This includes weather resistance and training mentioned before, but also a high degree of automation and safety, ease of use as well as extended flight times. It will be important to advertise and demonstrate the system convincingly. Furthermore, the crews that should use the system eventually should be involved early on in integration processes.

In conclusion, even though the major challenges of achieving a reasonable selling price and the targeted operators' and crews' trust remain, the drone system is generally perceived as useful, and the market seems to be open for such a system on the weather deck according to the results of our questionnaire.

10 SWOT Analysis

A strength, weaknesses, opportunities and threats analysis, in short SWOT analysis, is a strategic planning tool with the aim of identifying internal (strength, weaknesses) and external (opportunities, threats) factors that influence the expected outcome of a venture or project. It is often used as a basis for strategic decisions. In our case of the presented drone system, it can help to decide whether to pursue its productization. Our SWOT analysis takes the presented feasibility and usefulness analyses as main input. We further surveyed the main market trends in order to identify opportunities and threats. The results are shown in Table 6.

Table 6 SWOT Analysis

Strengths	Weaknesses
• Provided bird's-eye view is a unique and powerful feature in various situations • Can speedup localising missing person, fire detection and situational understanding, thus, save lives and protect property • Helps avoid human error in existing procedures • Technically feasible with off-the-shelf components and open standards • Drone system maintenance could be combined with other scheduled maintenance • Once installed, other use cases can effectively be supported: evacuation situations, inspections, supporting ship's navigation in difficult situations, … • The offshore context is quite challenging. Once "conquered", the system can further support applications along or on shore	• Requires a considerable investment • Regulation and integration are challenging and time-consuming • Introduces safety risks itself (esp. take-off and landing operations as well as charging) • Subject to weather, weather resistance is a cost factor • Monitors open decks only • Flight times are a limiting factor • High usability includes training and getting the crew used to the system. Otherwise, might be seen as a toy or distraction • Required manual interaction needs to be kept low, as much automation as possible • False alarms need to be kept at a minimum
Opportunities	**Threats**
• Drone technology is a fast-growing market, leading to lower required investments and better products • Drone servicing and repair is a fast-growing market, helping to keep OPEX low • Airspace regulations and management are under development, clearly specifying the integration of drone-base services • Maritime industry is increasingly digitized and going towards automation in general	• Revised maritime regulations (e.g., SOLAS) can strongly influence the interest of ship operators • Trust in the system is crucial but can be harmed by external influence and single negative events (e.g., news about an autonomous drone crashing into people)

Strengths

The drone system provides a unique and variable viewpoint that cannot be achieved with conventional video surveillance. Its agility combined with processing thermal and visual data help to speed up localising a missing person during search & rescue, detection of fire or fire risks during fire patrols, and understanding of situations during fire resource management. All of these use cases stress the drone system's main target of increasing overall safety by protecting property and lives. Of course, procedures exist for the mentioned use cases, but lack of information and the occurrence of human errors are problems that can be alleviated using the drone system.

As we have shown in this report, the drone system can be built with off-the-shelf components even today. More so, it can be built based on open standards for hardware, software and communication which guarantees future expandability and avoid any vendor lock-in. Without long-term tests, it is difficult to say how much maintenance will be required. Some maintenance will be required nonetheless (e.g., wear due to moving parts and weather influence), which can be performed during existing maintenance windows for other equipment on ship.

As a potential provider of the drone system, it is challenging to get into the market and achieve deployment of the drone system as a product. Once achieved, the deployed technology can effectively be adapted for additional use cases and services to extend the offer: evacuation situations, various inspections, supporting the ship's navigation in difficult situations (e.g., busy ports) and more. Considering the various challenges of the targeted offshore context, i.e., a moving vessel in all kinds of weather, the same system can be effectively adapted for use cases along or on shore, e.g., search & rescue missions starting from shore, and inspection services located at the port. Similar safety concerns targeted in this work can be found in non-maritime contexts as well, often where heavy machinery is used, e.g., in quarries, construction or forestry.

Weaknesses

Achieving a fully certified and tested product following applicable regulations will be time-consuming and costly. It is hard to estimate how much it will cost exactly, but it can be expected that the finished product can only be produced profitably if certification and testing costs can be distributed among a certain amount of deployments. Considering that the drone itself introduces safety risks, especially when taking off and landing (potentially even when charging), the amount of rigorous testing required should not be underestimated. In the previous chapter, we argued that weather resistance is an issue of cost, and this makes it additionally challenging to find the right selling price.

Functionally, the drone system as presented is limited to flying in open spaces. Even if thermal deviations can be seen through the ship's hull as shown in Figure 43, the usefulness of observing closed decks is limited. Further, flight times are limited, especially in battery-powered drones like the one presented in this report, where flight times under 60 minutes are expected (shorter under strong winds or cold weather). Potential solutions available today are a second drone, alternative power sources (e.g., hydrogen or petrol) or battery swaps optimized to a few minutes. None of these solutions seem ideal to us, though.

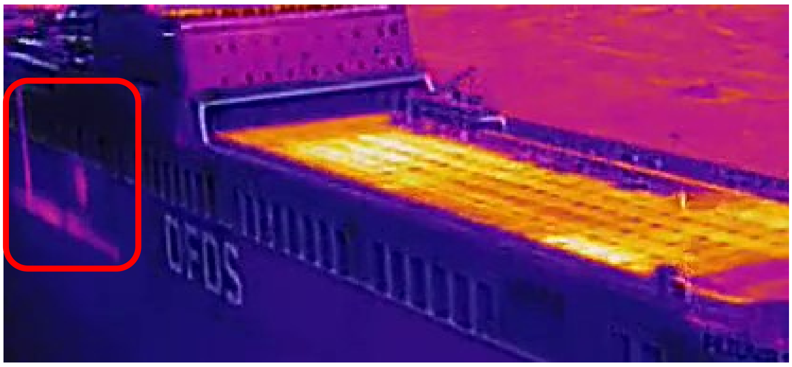

Figure 43 DFDS Petunia Seaway's bunker tank is clearly visible from a distance of approx. 150m in the thermal image

In order for the drone system to provide benefits, it is crucial for the crew to trust it and consider it as a help and not a burden. This entails that false alarms, e.g., warning for potential fires even if there is none, need to be kept at a minimum. Further, the crew will need to be well-trained and used to the drone to avoid the drone being seen as a distraction or toy. Ideally, the drone system would handle all kinds of situations autonomously, but clearly, at least some manual interaction will be required. While the possibility to control the drone was seen as helpful in our questionnaire, the required manual interaction should be kept at a minimum.

Opportunities

Several external developments increase the chances of seeing drone systems deployed on ships. Drone technology in general is a fast-growing market with a growing number of competing suppliers [47]. This drives down prices and fosters technological development leading to safer and better-performing products. It further includes a growing market of services around drone technology like drone servicing and repair [48]. Global networks of drone servicing providers provide the opportunity to outsource drone maintenance and help keep operational costs low. In parallel to these growing markets, more drone-supportive airspace regulations and management are emerging which specify the integration of drone-based services into airspaces and lower the hurdle for service providers to join the marked [29]. Again, this further safety of drone technology, as all sold drones from the beginning of 2023 need to be CE marked and specific standards, e.g., EN 4709, describe requirements for construction and design of drone systems.

Looking at the maritime industry, there is a strong drive for increased digitization and automation. This will further increase the acceptance of innovative technologies like drone systems and provide further opportunities to integrate digitized systems and provide more holistic services.

Threats

Conventions and regulations like SOLAS set minimum safety standards that ship operators are obliged to comply with. From our point of view, it is not realistic that drones specifically will become part of any safety standard for the foreseeable future. At the same time, revised and increased safety standards in general can mean considerable investments that need to be made. This means, if safety standards develop in a direction that makes it hard to cover safety requirements with the drone system or one that is incompatible, ship operators will lose interest in the technology. Eventually, this means that the potential provider of such a drone system needs to make sure that agencies like the IMO are aware of this technology and its benefits. At the very best, drone systems could in future be considered as one option to fulfil certain safety requirements.

We argued previously that trust in the drone system is crucial to convince ship operators and crews to deploy and use it. As automated drone systems are still an emerging technology, this trust can be volatile when tested, e.g., by headline news of major drone undertakings failing. A series of bad news like a drone crashing and harming people will most probably influence the willingness of a crew to accept working close to one. Therefore, rigorous testing and following (current and coming) regulations are naturally mandatory. Questions on safety and trust will surely arise while marketing the drone system and the potential provider of it needs to be prepared for it.

11 Conclusion

This report presents the feasibility and usefulness assessment of a drone system for surveying the open decks of a ro-ro ship, targeting the use cases of fire patrol, fire resource management and search & rescue operations. A prototype drone system is presented that is built on open standards and open-source software as far as possible for high extensibility and reproducibility.

The feasibility assessment is divided into technical feasibility and legal feasibility assessment. The technical feasibility is assessed in-depth using the drone system prototype including an in-house developed ground station to control the drone, which was designed specifically to assess the targeted use cases and is released as open-source software. In-field tests and a demonstration on board of DFDS Petunia Seaways are described. Unfortunately, on board assessments are limited to a single demonstration as a result of the COVID-19 pandemic. On-board assessments on a sailing vessel remain for future work. Further, we analyse potential interferences on the drone system's sensors and draw conclusions about the technical feasibility of a set of common requirements coming from the use case definitions. Overall, we evaluate technical feasibility positively but see the need for further development (automated landing on a sailing vessel), analysis (electromagnetic compatibility) and long-term tests (weather resistance and overall reliability).

The assessment of legal feasibility gives an overview of applicable maritime and airspace regulations within the EU. It concludes that operational authorization should be applied for in tight cooperation with a ship owner and a ship classification society in order to move forward effectively due to the given complexity. Generally, we do not expect the drone system to replace existing alarm systems, but to complement them.

An online questionnaire is a basis for the assessment of usefulness. It provides the responses from 34 maritime experts on the usefulness of the drone system for the three targeted use cases. All use cases were evaluated positively, with search & rescue missions being seen as the most promising for the drone system to improve. Two major challenges are identified during this assessment: achieving a reasonable selling price and obtaining the ship operators' and crews' trust in the system.

Finally, the SWOT analysis gives a concise summary of the performed assessments and can be used as input to the strategic business planning for a potential drone system provider.

In sum, this report provides comprehensive information for deciding whether to pursue the deployment of a drone system for increasing safety on ship. We show that designing such a system is possible with off-the-shelf components. It provides a unique bird's-eye view, can improve existing processes and ultimately contribute to saving lives and property. Maritime experts see the potential of the system and the market generally seems open to it. Future work will need to raise the TRL to level 7[32] by installing the system on a ship and performing long-term tests in operation. This will require tight cooperation with a ship operator and provide the required inputs for applying for operational authorization as well as achieving a conclusive cost estimate. Further, the system's benefits need to be made measurable in order to guarantee them under specified conditions. The hurdles for entry seem high but once ship operators and crews can be convinced, additional functionality, use cases and services can be added effectively, which provides an interesting business case for a potential drone system provider. Ultimately, proven benefits, cooperation with ship operators and communication with regulating entities are crucial to see drone systems successfully deployed on ships during regular operations.

[32] TRL 7 – system prototype demonstration in operational environment

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13 Indexes

13.1 Index of tables

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14 ANNEXES

14.1 ANNEX A – Safety Checklist

Visual inspection

1. Do you hear unusual noises from the propellers if you spin them with your fingers? Crackling sounds can indicate dirt in the engine's ball bearings and should not be ignored.
2. Are screws, brackets, joints or fasteners loose or damaged? Replace if necessary.
3. Are there any damage or cracks on the propellers? Never fly with damaged propellers.
4. Are there any loose or damaged cables?
5. Are there any loose or damaged connections?
6. Are propeller mounts, screws and propeller locks attached? (Feel for tightness.)
7. Never put stuff on the ground (propellers, HereLink, Laptop, ...) sooner or later you will step on it!

Preparations before start

1. Are the radio transmitter and batteries on board the drone fully charged?
2. Are there any frequency interference affecting video and receivers?
3. Is a compass calibration needed?
4. Is the photo and video equipment mounted correctly?
5. Is the starting point secured?
6. Are there any airspace restrictions on the drone map, NOTAM, AIP and AIP SUP?
   In addition to being able to check the current situation for your planned route in NOTAM and AIP, there is also the Civil Aviation Administration's (LFV) drone map
   https://dronechart.lfv.se/

   Information of a temporary nature, such as temporary restriction areas or other temporary restrictions, can be read in AIP SUP and in NOTAM.
   https://aro.lfv.se/Links/Link/ViewLink?TorLinkId=161&type=AIS
   https://aro.lfv.se/Editorial/View/IAIP
7. Start the radio transmitter first, then the drone and finally any other peripherals.
8. Are all levers in neutral?
9. Do the remote identification systems work as they should?
10. Apply a geofence around the flight zone
11. Pilot needs to get an ok from other participants before arming the drone.
12. Start!

In flight

1. Always keep your fingers on the radio transmitter.
2. Do not fly more than 120 meters above the ground (in uncontrolled airspace) and keep the drone in sight.
3. Rise to the optimal height to reduce risks or noise.

4. Avoid flying over people, animals, electrical wiring and buildings.
5. Do not interfere with ongoing rescue operations.
6. Immediately land the drone if a helicopter or other low-flying aircraft approaches.

Landing

1. Check the landing area so that there are no obstacles or any other danger.
2. Land the drone with a safe distance from obstacles and people.

After flight

1. Before going towards the drone, make sure that it’s disarmed and the pilot has given his ok.
2. Turn off the power to the drone
3. Visual inspection: look for damage and abnormal wear.
4. Remove the batteries, recharge them and store them in a safe place.